CONTENTS

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ORIGINAL
Ozone
Trend
Detectability

NASA

Ozone
Trend
Detectability

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National Aeronautics
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**Scientific and Technical
Information Branch**

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ii

PREFACE

This conference publication contains the proceedings of   ium on
Ozone Trend Detectability which was held in Boulder, Colorad   9, 1977.
The meeting was sponsored by the National Aeronautics and Sp   tion
to bring together experts in the fields of atmospheric scienc   tics
for the purpose of assessing our ability to detect anthropogenic   nces
in the Earth's ozone layer.

Two specific questions posed were (1) at what level and how quickly can
man detect a trend in total ozone using existing data sources, and (2) whether
there is any empirical evidence that the predicted depletion in total ozone
has already begun. A number of possible error sources, both within the data
measurements and in the modeling assumptions, were identified and discussed.
In particular, discussion focused on errors which are themselves subject to
trends, and an assessment of their significance was made.

The participants recommended that a multidisciplinary team be formed to
develop and improve models used for trend detection and to design measurement
programs tailored specifically to look for trends. Other recommendations
concerning time series models, the Dobson network, and future research are
detailed in this document.

Janet W. Campbell
Conference Chairman

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CONTENTS

SUMMARY OF SYMPOSIUM RESULTS

by

Janet W. Campbell

INTRODUCTION

A meeting of atmospheric scientists and statisticians was held in Boulder, Colorado, on July 28-29, 1977 for the purpose of addressing two questions related to ozone which remain unsettled despite recent assessments by the National Academy of Sciences (NAS) and the National Aeronautics and Space Administration (NASA). They are: (1) How quickly and at what level can scientists detect unnatural changes in the earth's ozone shield? (2) Is there any empirical evidence of the predicted depletion in total ozone? A structured program on the first day focused on the nature of existing ozone data (Session I) and trend estimation techniques currently being used (Session II). The second day was devoted to issue raising, discussion, and debate.

No quantitative, unanimous answer was found to the first question. Opinions of attendees as to the threshold of detectability (minimum change in ozone which one should consider significant) ranged from 1.5 percent, based on a time series analysis of Hill, Sheldon and Tiede (Geophysical Research Letters, January 1977), to approximately 6 percent, based on a conservative summing of several estimates. Because even the minimum threshold of 1.5 percent has not been observed in data sets since 1970, the answer to the second question, generally accepted by those present, is that there is no empirical evidence of a significant change in global total ozone. Some argue, however, that the trends predicted by modelers would be below our detection threshold and thus must not be ruled out.

Discussion and debate centered on three major issues: (1) the predictability of climatological series, (2) whether empirical models can be trusted, and (3) how errors in the Dobson total ozone data impact trend detectability. A number of recommendations for resolving the issues were also proposed. The issues and recommendations will be discussed separately.

ISSUES

The predictability of climatological series.- It is well known and documented by numerous examples that the character of a climatological series (its periodicities, amplitudes, etc.) can change abruptly after many years of stable variation. The reasons for such changes are not always understood. Thus, it would be a mistake to attribute automatically any observed change in global ozone to pollution or other anthropogenic

sources. Some concern seemed to be felt that any strictly empirical method, no matter how sensitive to ozone change, is inadequate because it cannot attribute changes to possible causes. These concerns were mitigated somewhat with assurances from statisticians that their empirical models would only be used as "early warning devices" to alert the scientific community of the existence of a change and the need for further study to determine its cause.

Some felt, however, that the "nonstationarity" of such time series was an insurmountable obstacle since it seriously degrades our predictive capability. The nonparametric approach presented by Marcello Pagano in Session II is of interest in this context. By this technique, a "trend" is said to appear when the capability of a model to predict one time step into the future diminishes significantly. That is, one observes how accurately a model predicts the time series used in its formulation (presumably this is the best it can do), and then one observes its predictive performance when applied to future time series. If this capability deteriorates seriously then a "trend" is said to have appeared in the future time series. Since, by this method, the ity of the predictive model is not as important as its consistency over time, this approach may have appealed to those who argued that no climatological model can be expected to have good predictive capability.

Empirical versus theoretical models.- As in most scientific research areas, the classical controversy arose between empirical methods ("let the observables speak for themselves") ard theoretical methods ("any observed behavior must have a theory to explain it"). Many examples were cited by the atmospheric scientists present of other physical processes whose variations are correlated to ozone variations. These included general circulation patterns and pressure fields, stratospheric winds, trade winds, ocean-atmosphere heat transfer patterns, atmospheric water vapor and temperature, energy sloshing and oscillations in the atmosphere, and others. Julius London estimated that between 50 and 100 papers have been published on the subject of correlating ozone to other phenomena. It was agreed by all, including the empirical modelers, that the inclusion of appropriate exogenous variables in ozone models should improve the models' ability to account for natural variability, thus making the models more sensitive to detecting abnormal changes in ozone. A divergence of opinion existed, however, as to how one determines whether or not an exogenous variable is "appropriate." John Tukey warned that two independent autocorrelated time series can appear to be highly correlated. Similarly, Elmar Reiter warned that like or equal periods in two physical processes (e.g., solar sector crossings and stratospheric ozone oscillations) need not imply a causal relationship between the two processes. Thus, one would need to exercise special care in the selection of exogenous variables. How one

2

decides which exogenous variables to include and how to bring them into a model are problems which, it was generally acknowledged, are difficult and need further study.

Impact of data errors on trend estimates.- One question which plagued many attendees concerns the relative size of the trends one is seeking (less than 0.5 percent per year) compared to the size of known errors in the data. One answer to this which was brought out at the meeting is that the "accuracy" of Dobson data, as a single quantitative measure, is not specific enough to reveal its impact on trend estimation. The impact of data errors depends on the nature of the errors, whether they are biases or random errors, and whether they are stationary or varying in time. Quite a number of possible error sources were identified and discussed. These included instrument problems such as slow drifts in the optical filter wedge, misaligned or nonparallel slits, temperature sensitivities, and stray light in the instrument. Other error sources involve the assumptions used in the data reduction algorithms, such as the assumed constancy of solar irradiance at the top of the atmosphere, the linearity (or flatness) of absorption and scattering coefficients with wavelength in the uv spectral range, and the failure to include other absorbing species which may be present in the atmosphere. Reid Basher made the important point that the only error sources which can seriously endanger trend estimates are those which can show trends themselves. Such error trends can either be mistaken for trends in the ozone when none exist or, if opposite in sign to existing ozone trends, can partially cancel real ozone trends so as to make their detection less likely or even impossible.

RECOMMENDATIONS AND SUGGESTED SOLUTIONS

The numerous suggestions and recommendations which emerged are listed below.

(1) Several changes to the time series models of Hill, Sheldon and Tiede were proposed in order to make them more acceptable to physical modelers.

(a) It was recommended that autocorrelations extending back beyond one year be avoided since these are highly controversial. This adjustment (concession) will increase the residual standard errors and consequently their estimates of the threshold of detectability. According to William Hill, this change is expected to be small.

(b) A suggestion to change the nine stations used as a global network was made on the basis that the ozone series at several of these stations are quite correlated. This objection may not be valid, however, because the method used by Hill, Sheldon and Tiede required only that the residuals of the nine

station models be independent--not that the original data series be independent. Hill and his associates are convinced that the residuals are independent.

(c) Another suggestion was that an exponential trend be estimated instead of a linear trend since the former is what the physical/chemical modelers predict to result from CFM releases. Hill stated that this was, in fact, done and that the results were virtually the same as with the linear trend model.

(2) Two recommendations were made to use the possible enhancement of trend detectability through the inclusion of exogenous variables.

(a) A bibliography on ozone and correlated physical processes should be compiled.

(b) A multidisciplinary team, including both statisticians and atmospheric scientists, should be formed to develop such a model or at least to propose the list of appropriate exogenous variables to be included.

(3) Recommendations concerning the Dobson network/data numbered two.

(a) Serious consideration should be given to the "archeology" of Dobson data records and their recalibration for the purpose of determining low frequency oscillations and possible trends. Since these are the only long-term records on ozone in existence, we should do the best job possible with the interpretation of these series.

(b) Some assessment of the value of a future Dobson network should be made and this value weighed against the resources used to support it. The latter should be made compatible with the former.

(4) Recommendations relating to the data errors also numbered two.

(a) A detailed error analysis should be made in which every important error source is identified, examined for possible trends, and the sensitivity of ozone trend estimates to these errors determined.

(b) Where error sources are shown to have possible trends, these sources should be eliminated or a means of estimating their trends devised. It was suggested that such a scheme will probably include the use of independent instruments and/or measurement techniques (such as those afforded by satellite instruments).

(5) Experiments or analyses tailored specifically to look for trends were suggested. Generally these involve a maximizing of signal-to-noise in a sense. Two specific examples are listed here.

4

(a) A very promising possibility is to monitor ozone in the 40 to 45 km altitude region. Natural variability is quite small at these heights, whereas CFM-related depletions are expected to be much greater here than in the total column.

(b) Another possibility is to restrict our analyses to a single season such as the summer season during which natural variability is low. This approach would look for trends from year to year in that season. Seasonal effects will be automatically eliminated and natural intra-seasonal variability will be minimized by the choice of season.

CONCLUDING REMARKS

The meeting of statisticians and atmospheric scientists involved in the ozone trend detectability problem was characterized by a spirit of cooperation between the two groups and an expressed willingness to work together to gain answers to the questions posed. Although the physical scientists, in general, still remain somewhat distrustful of empirical methods which exhibit no physical insight, they came to realize, hopefully, that the statisticians using these methods do have physical insight and, therefore, the statistical tools are not being applied blindly.

The statisticians came away with better physical understanding generally and, perhaps, a better appreciation for the fact that the ozone data used in their models are contaminated measurements subject to a number of errors. Those fearful of the errors in Dobson data were assured somewhat that not all errors present serious obstacles to accurate trend estimation. Nevertheless, some errors, specifically those subject to trends themselves, can present serious problems. The recommendation was therefore made to identify and quantify, if possible, those serious error sources and either eliminate them or correct for their presence. Other recommendations involved the careful archeology of Dobson data to make the best use of our major (only) resource for finding trends, the inclusion of appropriate exogeneous variables into ozone models to account for natural variability, and modifications to the time series trend analysis which might make it more palatable to the physically-oriented modelers.

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INTRODUCTION

Stratospheric ozone is one of many trace elements found in the band of atmosphere which encompasses the earth at an altitude of 8 to 50 km. Although the concentration of ozone is small (a few ppm at most) it plays an important role in the life cycle on earth. By absorbing nearly all solar ultraviolet (uv) radiation with wavelengths less than 290 nanometers as well as most uv radiation in the 290-330 nanometer region, the "ozone layer" shields the earth from most of the harmful uv radiation. A depletion of the ozone would allow increasing amounts of harmful uv radiation to reach the earth's surface. This radiation could adversely affect plant, animal and human life as well as cause changes in the climate.

The ozone layer is a naturally dynamic system in which ozone molecules are constantly being created and destroyed. Recently, considerable attention has been focused on the effect of human-related activities on the ozone equilibrium. It has been hypothesized that the release of various chemical compounds into the environment, such as anthropogenic halogens, nitrogenous fertilizers, and emissions from subsonic and supersonic aircraft have caused and will continue to result in ozone depletion. Of particular importance is the effect of the release of chlorofluoromethanes (CFMs) FC-11 and FC-12 since these compounds are widely used in aerosol products, air conditioners, refrigerators and urethane foam manufacturing.

Recently a panel of scientists from the National Academy of Sciences (NAS) attempted to quantify the level of the hypothesized depletion of ozone. On the basis of their research, the NAS panel concluded that the continued release of FC-11 and FC-12 at the 1973 rates "...would cause the ozone to decrease steadily until a probable reduction of about 6 to 7.5% is reached, with an uncertainty range of at least 2 to 20%."

Because of the slowness of the decline (0.07%/year with a range 0.02-0.20%/year), half of the hypothesized depletion in total ozone, a measure (in milli atmosphere-centimeters) of the amount of ozone in a column of air stretching through the atmosphere, would be predicted to take 50 years. This is not necessarily true at all altitudes. For example, the changes at 40 km are far larger--perhaps an order of magnitude--than any changes in the more usually measured total ozone.

Total ozone concentrations are currently measured at approximately 80 sites throughout the world. Although total ozone measurements have been recorded as far back as 1926 (Arosa, Switzerland), most recording stations began monitoring ozone in the late 1950s or early 1960s. Generally from one to five observations are made per day using a Dobson-type spectrophotometer or a filter ozonometer, weather permitting.

SESSION I: THE NATURE OF THE DATA

Julius London presented a "tutorial overview" which began with a display the locations of total ozone stations (Fig. 1) and of stratospheric ozone samp lings (Fig. 2). The samplings are largely concentrated in three areas--Japan, Europe, and India. Approximately 75% of the total ozone measurements are made with Dobson instruments which offer the best international measurements. If th are well cared for and well calibrated, their accuracy is on the order of a
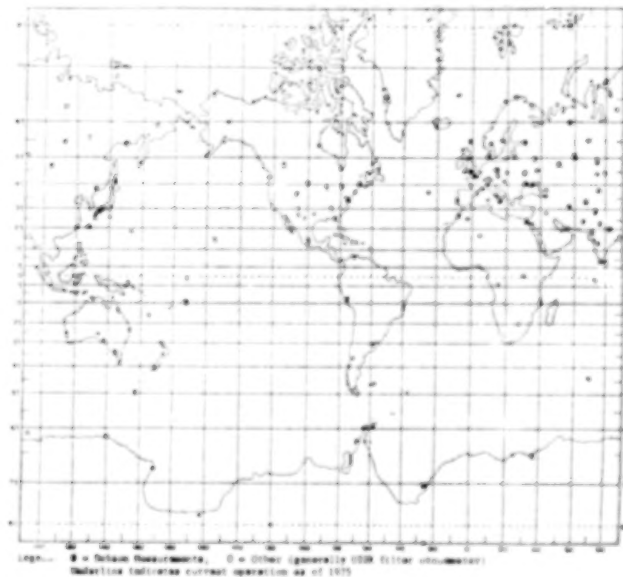

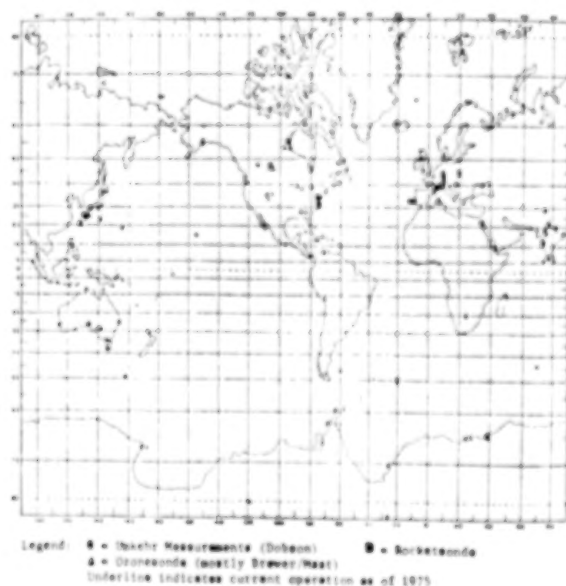Figure 1.   Location of Total Ozone Stations (1957-1975)

Figure 2. Observations of Stratospheric Ozone (1957-1975)
(non-satellite)

few percent. Long period observations made with the same instrument have "relatively good" reproduction and reliability. The remaining 25% of the world's observations are made with filter instruments which were very noisy until the USSR improved them substantially in 1969. "Now," London said, "they are noisy rather than notoriously noisy."

Plotting the available data produces a picture of global distribution of total ozone (Fig. 3) that shows an equatorial minimum and an increase toward the polar regions. These features of the ozone distribution are both well-known. Variations in total ozone amount depend on season and latitude. This can also be seen in variance data from individual stations (Fig. 4).
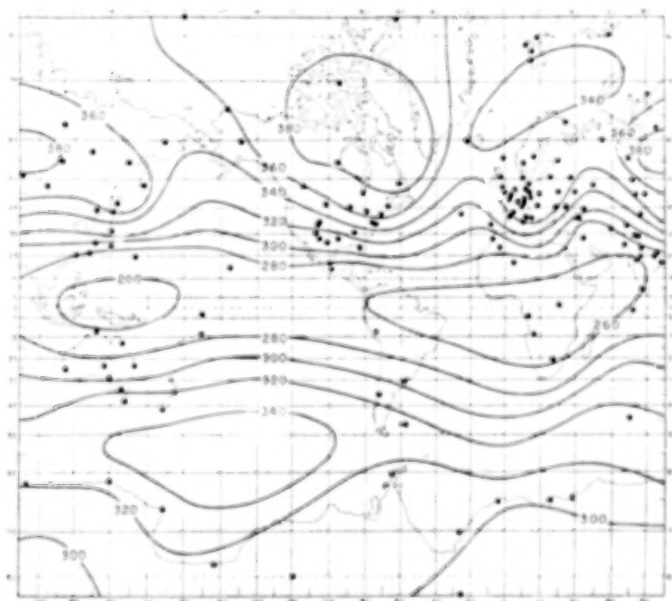
Figure 3. Distribution of Total Ozone for the Period 1957-1975 (m atm-cm)

Although the total ozone pattern is similar in both hemispheres, the northern hemisphere has 3 to 10% more total ozone than the southern hemisphere, not a negligible amount, according to London.

In the stratosphere, the hemispheric difference is even more pronounced as mid-latitude eddy transport is stronger in the northern hemisphere than in the southern. The maximum ozone concentration that occurs in the lower stratosphere varies with latitude and season. (In the summer and at the equator, the maximum is higher than in the winter and at the poles.)

London noted the "close association" between total ozone distribution and pressure distribution in the atmosphere. High amounts of ozone are clearly associated with large scale troughs in pressure distribution.
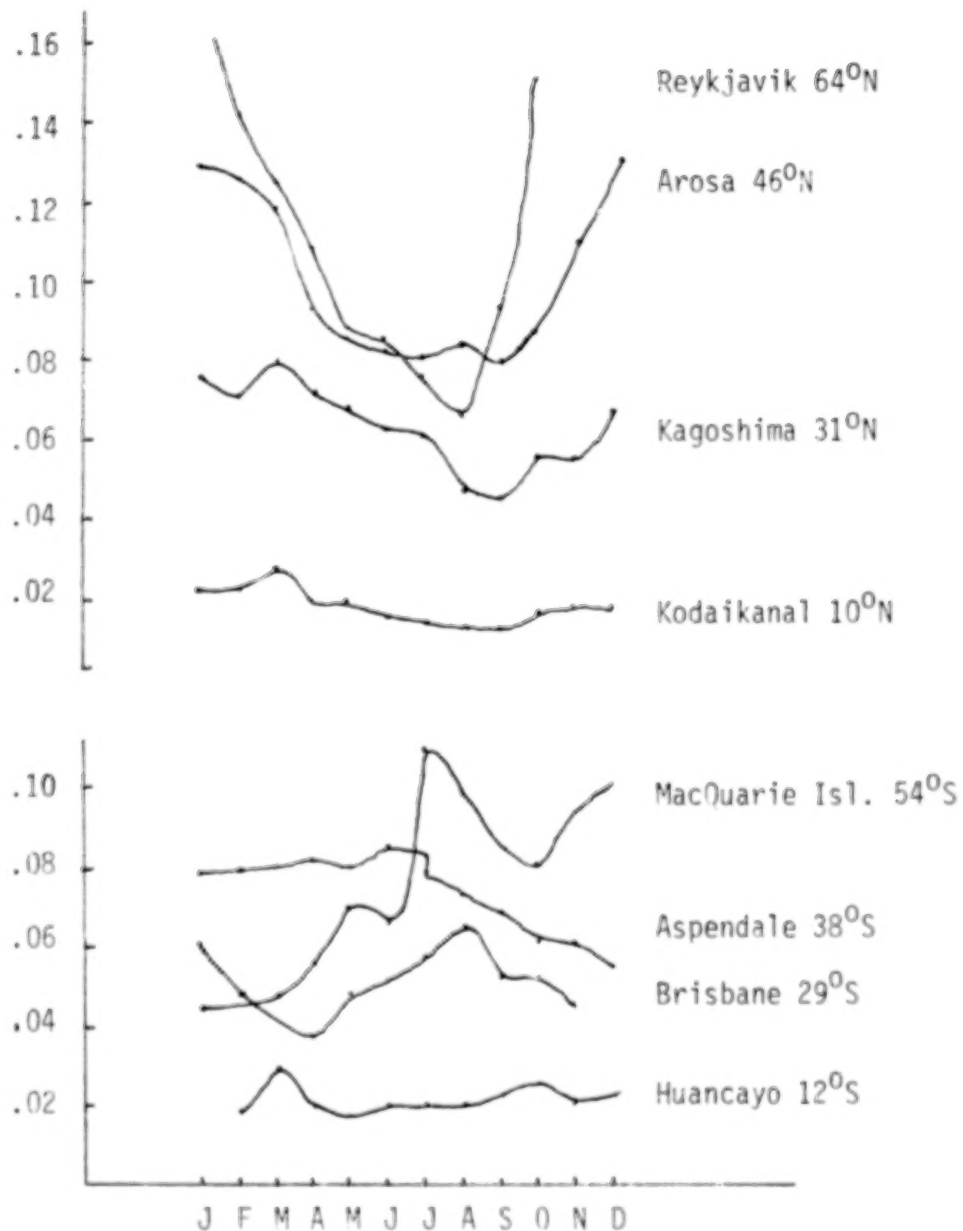
Figure 4. Seasonal and Latitudinal Variations in the
Variance of Ozone Data

Displaying the average latitude seasonal variation (Fig. 5) shows the well-known spring maximum that is stronger in the northern hemisphere than in the southern. This spring maximum is also delayed a month in the south, a fact that London said was "more evidence of the relationship between ozone concentration and circulation" because it reflected the longer relaxation time in terms of the atmospheric circulation.
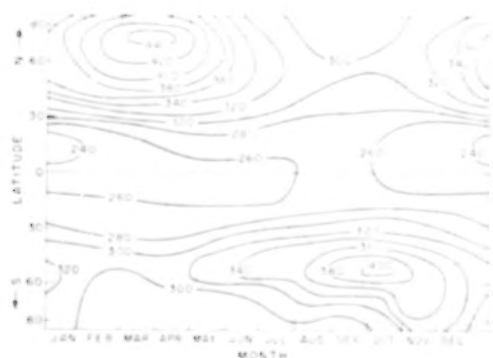
Figure 5.   Average Latitude Seasonal Variation of Total Ozone
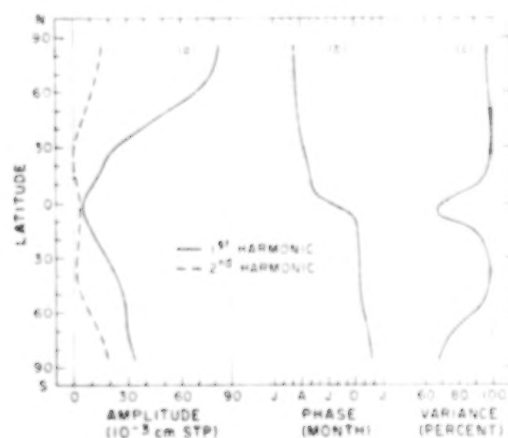
Figure 6.   Latitudinal Distribution of the Harmonic Parameters
of the Ozone Variation

To further reinforce his point that the variance of total ozone concentration is very like the behavior of the lower stratosphere and therefore the result of meteorological parameters, London fitted the mean monthly latitude values of ozone to the first harmonic (annual cycle) and second harmonic (phase) of the annual ozone variance (Fig. 6). Four different comparisons of these data (Fig. 7) then further supported his thesis.

Several statistical scientists commenting on their own efforts to smooth out the seasonal variance noted that: the variance of the reciprocals is less than that of the Dobson data; and nothing really stabilizes the variance although the reciprocal is better than the logarithm.
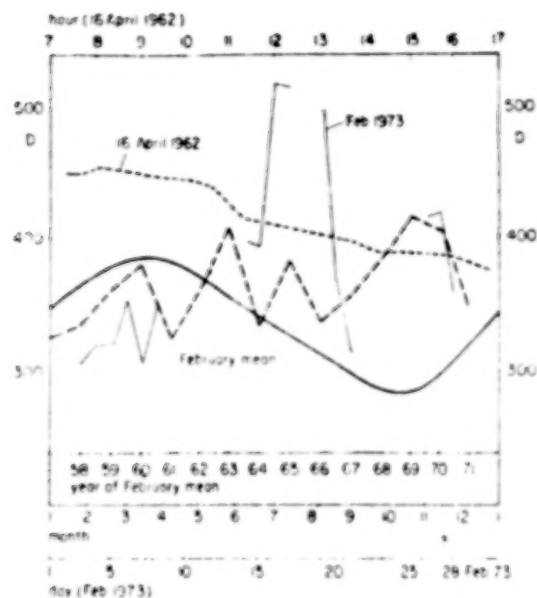
Figure 7. Comparison between the seasonal variation (monthly mean values) (————), the day-to-day changes within 1 month (February 1973), given by daily mean values (————), possible variation within 1 day (16 April 1962, single readings) (- - - - - -), and the differences between mean values of the same calendar month (February) from year to year) (— — —).
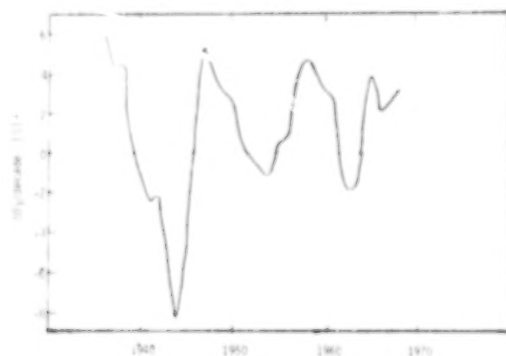
Figure 8. Ten Year Running Trend, Arosa, 1932-1973 (monthly means)

London then presented data from a single station, Arosa, Switzerland, where total ozone measurements have been made since 1926. These data (Fig. 8) indicate a long-term change of 6%, about half the standard deviation.

Walter Komhyr presented detailed information about Dobson measurements and the various algorithms used to calculate total ozone. The Dobson spectrophotometer (Fig. 9) takes in light from the direct sun or the zenith sky. The measurement principle requires measuring the ratio of intensities of solar radiation I/I' at pairs of wavelengths, λ and λ' (Fig. 10).

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Incident light

Window (w)

Collecting lens   uv filter

Slit (S_5)   Slit (s_1)

Compensating   Wavelength   Lens (L_1)
adjustment (Q_2)   adjustment (Q_1)

M_2 L_2 Mirror (M_1)

Slit (S_2)

P_2 Prism (P_1)

Achromatising lens   Achromatising lens
Collecting lenses   Optical wedges

S_3

S_4

Spindle carrying
sector wheel and
commutator

Rotating sector
wheel

Plate either
passing or
obscuring
beams from slit
S_4; also holds
rhodium plate

Sector plate passing
light from either
S_2 and S_3 or S_3 and S_4

Figure 9. The Optical System
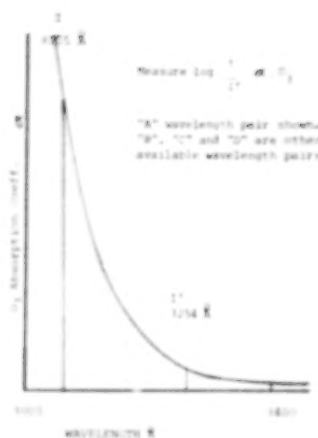
Figure 10.   Ratio of Intensities of Solar Radiation I/I' at Pairs
of Wavelengths, λ and λ'

Total ozone x is then calculated from the following equation:

$$x = \frac{L_0 - L - (\beta - \beta')mp/p_0 - (\delta - \delta')\sec Z}{(\alpha - \alpha')\mu} \qquad (1)$$

where $L = \log(I/I')$;

L_0 is the value of L at the top of the atmosphere;

α and α' are ozone absorption coefficients;

β and β' are molecular scattering coefficients;

δ and δ' are particle scattering coefficients;

μ is the slant path of light through the ozone layer;

m is the air mass;

p and p_0 are mean station pressure and mean sea level
pressure, respectively;

and   Z is the solar zenith angle.

The ozone absorption coefficients used before 1956 were
36% different from those currently set by the International
Ozone Commission (Fig. 11).

Designation of wavelength pair		Mean wavelength λ_μ		Equivalent Instrument Slit widths λ_μ		Atmospheric Scattering Coefficients (Rayleigh Cabannes formula)		Ozone Absorption Coefficients		
								Adopted for use July 1, 1957*	Adopted for use January 1, 1968**	
						β	β'	α	$\alpha-\alpha'$	$\alpha-\alpha'$
							$\beta-\beta'$	α'		
A	Short	3055		9		0.891		1.802	1.762	1.748
	Long		3254		20		0.375			
							0.116	0.720		
B	Short	3088		9		0.470		1.267	1.273	1.145
	Long		3291		20		0.357			
							0.113	0.064		
C	Short	3114.5		9		0.453		0.912	0.865	0.800
	Long		3324		20		0.352			
							0.110	0.067		
D	Short	3176		9		0.417		0.391	0.374	0.360
	Long		3398		20		0.312			
							0.104	0.017		
C'	Short	3324		10		0.343		0.047	0.047	
	Long		4536		15		--			
							--	+11		
AD							0.012		1.388	1.388
BD							0.009		0.889	0.760
AC							0.008		0.897	0.949
CD							0.006		0.491	0.440

*From July 1, 1957, the values of α are based on 1953 results of Vigroux for -44°C, which are about 3% smaller than the values of Ny and Choong used previously.

**Based on coefficients remeasured by Vigroux in 1967 as well as on atmospheric measurements, and recommended for use by the IAMAP.

Figure 11.   Dobson Spectrophotometer Wavelengths and Constants

Solution of equation (1) involves dealing with the usually unknown term $(\delta - \delta')$. In practice, therefore, observations are made on double pair wavelengths in which case the particle scattering term becomes $(\delta - \delta')_1 - (\delta - \delta')_2$. To a good approximation, this quantity is assumed to equal zero. The equation for computing ozone using two wavelength pairs is

$$x_{12} = \frac{[(L_0-L)_1-(L_0-L)_2]-[(\beta-\beta')_1-(\beta-\beta')_2]mp/p_0-[(\delta-\delta')_1-(\delta-\delta')_2]\sec Z}{[(\alpha-\alpha')_1-(\alpha-\alpha')_2]\mu} \quad (2)$$

The most commonly used wavelength pairs are the A and D pairs and this equation is

$$x_{AD} = \frac{(L_0 - L)_1 - (L_0 - L)_2}{1.388\mu} - \frac{0.012mp}{\mu p_0} \quad (3)$$

Values for L, β, β', α, α', μ, m, p and p_0 are obtained using laboratory or other techniques. Calibration, i.e., measurements on direct sun, are needed to obtain L_0. The following equations describe the procedure for calibrating Dobson ozone spectrophotometers on an absolute scale.

Method 1. (Langley Plots). For observations made on clear days when $(\delta - \delta') = 0$, equation (1) can be rewritten

$$L + (\beta - \beta')mp/p_0 = -(\alpha - \alpha')\mu x + L_0 \tag{4}$$

which is linear in μ of the form $y = a\mu + b$ provided that x remains constant during the observing interval. By plotting $L + (\beta - \beta')mp/p_0$ against μ (for $0 \le \mu \le 3.2$) and fitting a line to the data, the slope is $a = -(\alpha - \alpha')x$ and the intercept is $b = L_0$. In this manner the extra-terrestrial constant, L_0, is determined for the instrument.

Method 2. (Slope Method). Equation (1) can also be written

$$L_0 - L - (\beta - \beta')mp/p_0 = (\alpha - \alpha')\mu x + (\delta - \delta') \sec Z \tag{5}$$

Let L_0^* be the assumed approximate value of L_0, L_0 be the true value, and define $S = L_0 - L_0^*$. Then the equation

$$\frac{L_0^* - L - (\beta - \beta')mp/p_0}{\mu} = \frac{-S}{\mu} + (\alpha - \alpha')x + (\delta - \delta')\frac{\sec Z}{\mu} \tag{6}$$

is linear in $1/\mu$. Plotting the left hand side of equation (6) against $1/\mu$ gives the slope $a = -S$, and the intercept is $b = (\alpha-\alpha')x + (\delta-\delta')$ for $\sec Z \approx \mu$. The estimate of S is then used to correct the estimated L_0 value.

The primary standard Dobson spectrophotometer (instrument #83) was used as a reference instrument for a World Meteorological Organization-sponsored International Comparison of Dobson Ozone Spectrophotometers Meeting held in Boulder, Colorado, August 8-19, 1977. Regional secondary standard instruments from Australia, Canada, East Germany, Egypt, Japan, the United Kingdom, and India were compared with reference instrument #83.

A summary of similar instrument comparisons held in the past was presented by Komhyr (Fig. 12).

1. Hungary, 1969:

    5 Eastern European Dobson instruments compared

    2 groups insts. $\Delta O_3 \sim 10\%$

    Discrepancies exceeding 20%

2. Belsk, Poland 1974 *:

Inst. No	ΔN_{AD}	Δx_{AD}, x=0.300 cm			% error in x		
		$\mu=1$	$\mu=2$	$\mu=3$	$\mu=1$	$\mu=2$	$\mu=3$
41	0.016	0.012	0.006	0.004	3.8	1.9	1.3
64	0.108	0.079	0.039	0.026	26.3	13.0	8.7
77	-0.023	-0.017	-0.008	0.006	-5.5	-2.8	-1.8
83*	0	0	0	0	0	0	0
84	0.056	0.040	0.020	0.013	13.5	6.7	4.5
96	0.002	0.001	0.001	0	0.5	0.2	0.1
101	0.018	0.013	0.006	0.004	4.3	2.2	1.4
108	0.025	0.018	0.009	0.006	6.0	3.0	2.0
110	0.051	0.037	0.018	0.012	12.3	6.1	4.1
112	-0.024	-0.017	-0.009	-0.006	-5.8	-2.9	-1.9

*Spectrophotometer No. 83 was the reference instrument for the comparisons.

Figure 12. Results of Past Dobson Instrument Comparisons

Komhyr then presented data on additional absolute calibrations of U.S. standard spectrophotometer #83 that were made in 1962 and 1972. He also presented an analysis of the data which illustrated a method whereby possible variations in L_o values for the A, C, and D wavelength pairs may be detected. Such variations, for example, may occur with variations in sunspot numbers.

Komhyr concluded his presentation by examining the effect of possible changes in L_o with time on the accuracy of ozone measurements. He examined three cases:

<u>Case 1</u>: Single pair wavelengths A, B, C, D

$$x = \frac{L_0 - L - (\beta-\beta') \, mp/p_0 - (\delta-\delta') \, \sec Z}{(\alpha-\alpha')\mu}$$

$$\Delta x = \frac{\Delta L_0}{(\alpha-\alpha')\mu} \quad \text{where} \quad x_{true} = x_{meas.} + \Delta x$$

.
.
. . If L_0 <u>increased</u> during the 1960's, measured O_3 amounts were too low.

Assume:

$$\Delta L_{0 \; 1976\text{-}1962} = 0.015 \text{ and } x = 0.300 \text{ cm.}$$

Then using:

$$\Delta x_A = \frac{0.015}{1.748\mu} \qquad \Delta x_C = \frac{0.015}{0.800\mu} \qquad \Delta x_D = \frac{0.015}{0.360\mu}$$

% Error in x			
μ $\qquad$ $\lambda\lambda$	A	C	D
1	2.9	6.2	13.9
2	1.4	3.1	7.0
3	1.0	2.1	4.6

<u>Case 2</u>: Double pair wavelengths AD, CD

$$x_{AD} = \frac{L_{oA} - L_{oD} - L_A - L_D - [(\beta-\beta')_A - (\beta-\beta')_D] \, mp/p_0}{[(\alpha-\alpha')_A - (\alpha-\alpha')_D] \, \mu}$$

$$\Delta x_{AD} = \frac{\Delta L_{oA} - \Delta L_{oD}}{[(\alpha-\alpha')_A - (\alpha-\alpha')_D]\mu} = \frac{\Delta L_{oA} - \Delta L_{oD}}{1.388 \, \mu}$$

Assuming that for the time interval 1962 to 1976

$$\Delta L_{oA} = 0.0154 \qquad \Delta L_{oD} = 0.0141 \qquad x = 0.300$$

$$\Delta x_{AD} = \frac{0.0013}{1.338 \; \mu}$$

% Error in x_{AD}	
$\mu = 1$	0.3
$\mu = 2$	0.2
$\mu = 3$	0.1

Komhyr pointed out that if it is assumed that solar irradiance variations occur exponentially in the uv region of the solar spectrum, then errors in total ozone measurements resulting from L_o variations are insignificant when observations are made on double pair wavelength such as the AD pair which is the usual practice. However, observations made on single pair wavelengths could be significantly in error.

Case 3:   CC' Observations

These are ozone observations made on the zenith sky using C wavelengths.

For $\Delta L_{oC} = 0.015$ and $x = 0.300$

% Error in $x_{CC'}$	
$\mu = 1$	4.0
$\mu = 2$	2.7
$\mu = 3$	2.0

Thus the errors in CC' observations due to solar intensity variations in the uv region of the solar spectrum can be appreciable.

Reid Basher then discussed systematic errors in Dobson measurements. He pointed out that the measurements are always in error to some extent, as a result of such things as aerosol scattering character, other atmospheric absorbing species, stratospheric temperature, instrument temperature, solar zenith angle, and solar spectral irradiance, but he noted that only those with long-term periodicities are important.

Instrument-related errors can be controlled by regular, rigorous calibration, but, in practice, this may be difficult, and not all errors will be known or appreciated. Atmosphere-related errors - attenuation by aerosols, absorption by other species such as SO_2 and NO_2, dependence of ozone absorption on temperature, and variations in the effective mean height of the ozone layer - can conceivably have long-term periodicities. For example, atmospheric particulate loading rises sharply with volcanic activity and decays with a relatively long half-life. These variable error sources will probably need to be monitored simultaneously in order to attain a high ozone trend detectability.

Basher selected as an example the case of atmospheric aerosols, particulates, and absorbers, explaining as follows:

Since the measurement between a pair of wavelength bands is a differential one, only relative effects are important, e.g.:

$$\log \frac{I_1}{I_2} = \log \frac{I_{o1}}{I_{o2}} - \mu X (\alpha_1 - \alpha_2) - m (\beta_1 - \beta_2) - \sec Z (\delta_1 - \delta_2)$$

measurement   extraterrestrial constant   ozone   molecules   aerosol

$$- (\gamma_1 - \gamma_2)$$

other

Consider the effect of aerosol attenuation. If the effect is spectrally flat, $\delta_1 = \delta_2 = \delta(\lambda_0)$, it is eliminated directly within a band-pair measurement. If it is spectrally linear, $\delta_1 = \delta(\lambda_0) + g_1(\lambda_0 - \lambda_1)$, a third wavelength band or second band-pair is needed to eliminate the error.

For a quadratic dependence, $\delta_1 = \delta(\lambda_0) + g_1(\lambda_0 - \lambda_1) + g_2(\lambda_0 - \lambda_1)^2$, four wavelengths or three band-pairs are needed to eliminate the error. The standard Dobson measurement, X_{AD}, is a two band-pair measurement and thus deals effectively with spectrally linear effects (due to aerosols or other absorbers), but it will be in error if the effects are spectrally non-linear (Fig. 13).
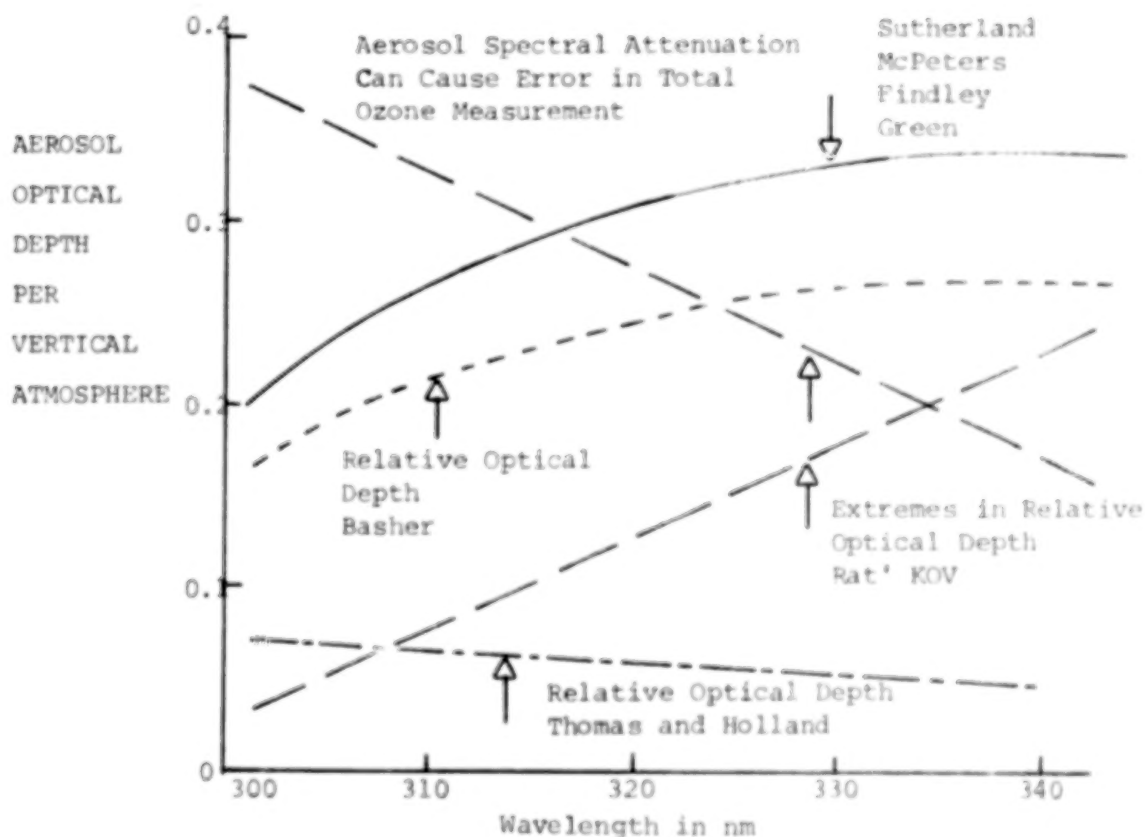
Figure 13. Atmospheric Aerosol and Total Ozone Measurement

Experimental measurements of atmospheric extinction indicate that sometimes there are significant spectral nonlinearities, with $g_2 \sim 4 \times 10^{-5}$, and consequent errors in X_{AD} of 5%. There is no firm agreement on this problem, since the experimental determination of g_2 is not very accurate, and theoretical calculations indicate that rather unusual types of aerosols are needed to produce the nonlinearities. The effect might well be due to an absorbing species.

One species which does absorb in the uv is NO_2. Fortunately, its absorption spectrum is reasonably linear so that its error component is largely eliminated by the double wavelength pair X_{AD} measurement. For a single wavelength pair, though, errors of many percent can arise where NO_2 concentrations are high, e.g. 40 ppb averaged over an atmospheric column. Typical values are 1 - 10 ppb, according to Basher. Further study is needed to assess the spectral non-linear extinction of aerosols and atmospheric trace species, as well as the long-term variability of the spectral character.

Basher then discussed a model of stray light (Fig. 14) that indicates a possibility of errors of several percent in the Dobson instrument, "always an underestimate." The error arises from the interaction of instrument and atmosphere, and is dependent on the instrument's sensitivity to the stray light, as well as the solar zenith angle and the atmosphere's ozone content. The instrument dependence can change slowly with time so a regular monitoring or correction of stray light is needed to avoid giving the appearance of long-term change in ozone. However, Basher concluded, the dependence of the stray light error on zenith angle and ozone itself simply adds an extra amplitude to the already existing yearly cycle term and is thus of no consequence.

Examining the case of calibration errors, Basher noted that calibration basically consists of ensuring constancy in the wave-lengths of the bands and determining each band-pair's relative spectral output in the absence of the atmosphere, that is, deter-minining extraterrestrial constants. The first part involves simply a comparison with some stable wavelength standard. From the point of view of trend detection it is desirable to do this at least once a year. Quite rough wavelength calibrations would even be acceptable if they were made frequently and the "roughness" were random. The second part of the calibration is probably the most difficult aspect of ground-based total ozone measurement. For such measurements the "absence of the atmosphere" can only be gained indirectly, and the field measurements involved are time consuming and give inconsistent results that reflect as much as several percent variation in ozone measurements.

Basher reinforced Komhyr's point that the solar near-ultraviolet relative spectral irradiance may not be constant. For trend analysis, extraterrestrial constants need to be constant but not necessarily accurate. The instrument component of the constants can be cali-brated with standard lamps, although past experience has shown this to be no easy task. The measurement of the solar uv component of the extraterrestrial constants requires an extra-atmospheric instrument location. The stability of this calibrating instrument must be better than the suggested 0.3% per year sensitivity of the ozone

X$_{AD}$

Total Ozone

ATM-CM

Ozone Error

2 ———————————————— 1

1 —————————————————— 2

} 'True' Ozone of Models 1 and 2.

Model 2 Has Larger Extraterrestrial Constant Error.

○ Data Is Mean Dependence Of Experimental Wallops Dobson Total Ozone

Stray Light Models Predict Underestimates Of 3% To 10% In Wallops Total Ozone.

Relative Constancy In Measurements Over Normal Operating Range (Airmass 1 to 3) Conceals the Large Actual Error.
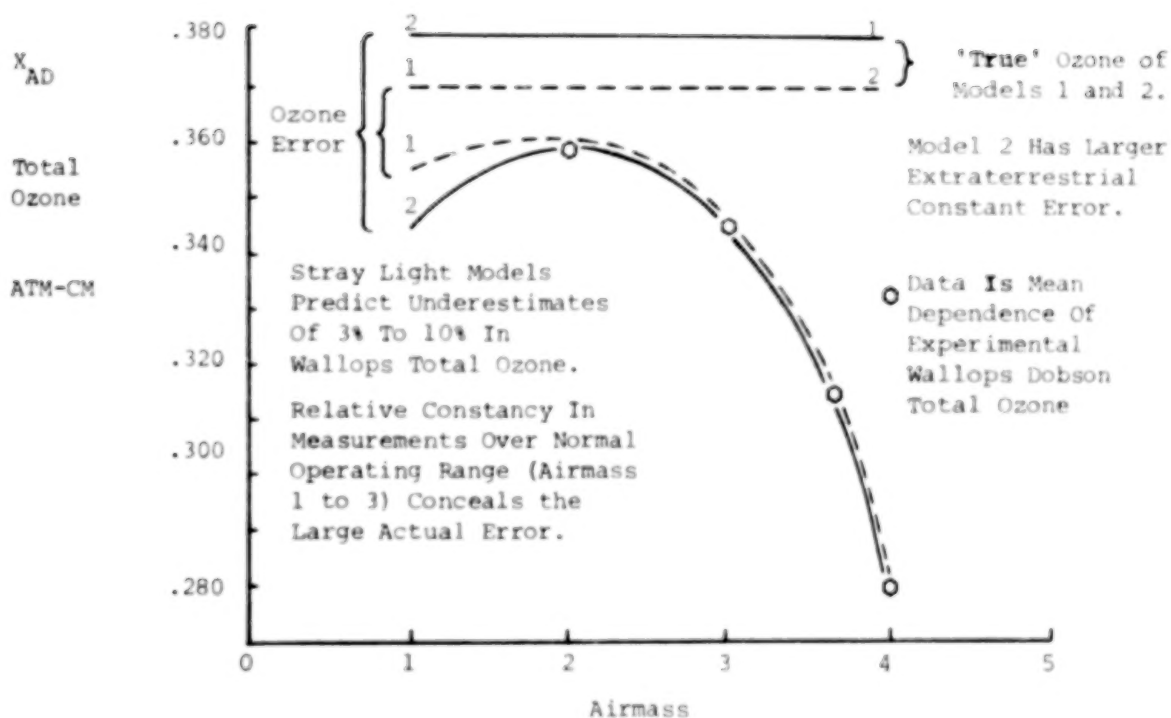
Airmass

Figure 14. Model of Stray Light Error in Dobson Total Ozone

trend detection method; that is, it must be stable to less than
0.2% per year in relative spectral response. Moreover, there
must exist means to independently verify the stability on a
continual basis. Basher said, "The fact that at present such
long-term stability is very difficult to achieve, even in the
laboratory, should not completely discourage the consideration
of preliminary remote space experiments."

In conclusion, Basher noted, "Our present lack of knowledge
of the effects of aerosol attenuation and of other absorbers on
the ozone measurement and our lack of certainty about the extra-
terrestrial constants' constancy severely limit our ability to
interpret measured trends as real ozone variation. It is quite
possible that aerosols have no significant effect on X_{AD} total
ozone, that the uv solar spectrum is particularly constant, and
that the 0.3% per year detectability limit is meaningful. However,
until we can prove these things we must accept a large uncertainty
in trend detection results, probably more than 1% per year. Of
course a good deal more study of systematic errors is needed."

Donald Heath next discussed satellite measurements of ozone
using the nadir-looking BUV (Backscattered Ultra-Violet) instru-
ment on NIMBUS 4, which was launched in 1970. This instrument is
producing data at what Heath termed a cost of "about a dollar
each over the life of the satellite, including original cost"
(Fig. 15). NIMBUS G planned for 1978 as well as the TIROS N
series may carry similar instruments.

The BUV instrument measures the ultraviolet solar radiation
which is backscattered by the earth and its atmosphere and compares
this, at varying wavelengths between 2550 and 3400 angstroms, to
the incoming uv radiation (Fig. 16). The data are used to estimate
both vertical profiles of ozone down to the 0.2 millibar level and
total ozone. The data inversion technique requires a statistical
quantity for P*, the pressure height of the maximum ozone level as
a function of latitude and season. Balloon and rocket data help
provide upper and lower first guesses (Fig. 17).

So far total ozone data have been released for the first year
of the satellite's mission and these data are currently undergoing
a revision based on improved calibration of the instrument.

"We need guidance to determine long term instrument perfor-
mance," said Heath. He then went on to discuss the puzzle of know-
ing which Dobson instruments to use for ground truth. Integrating
data over the whole globe, he compared BUV and Dobson measurements.
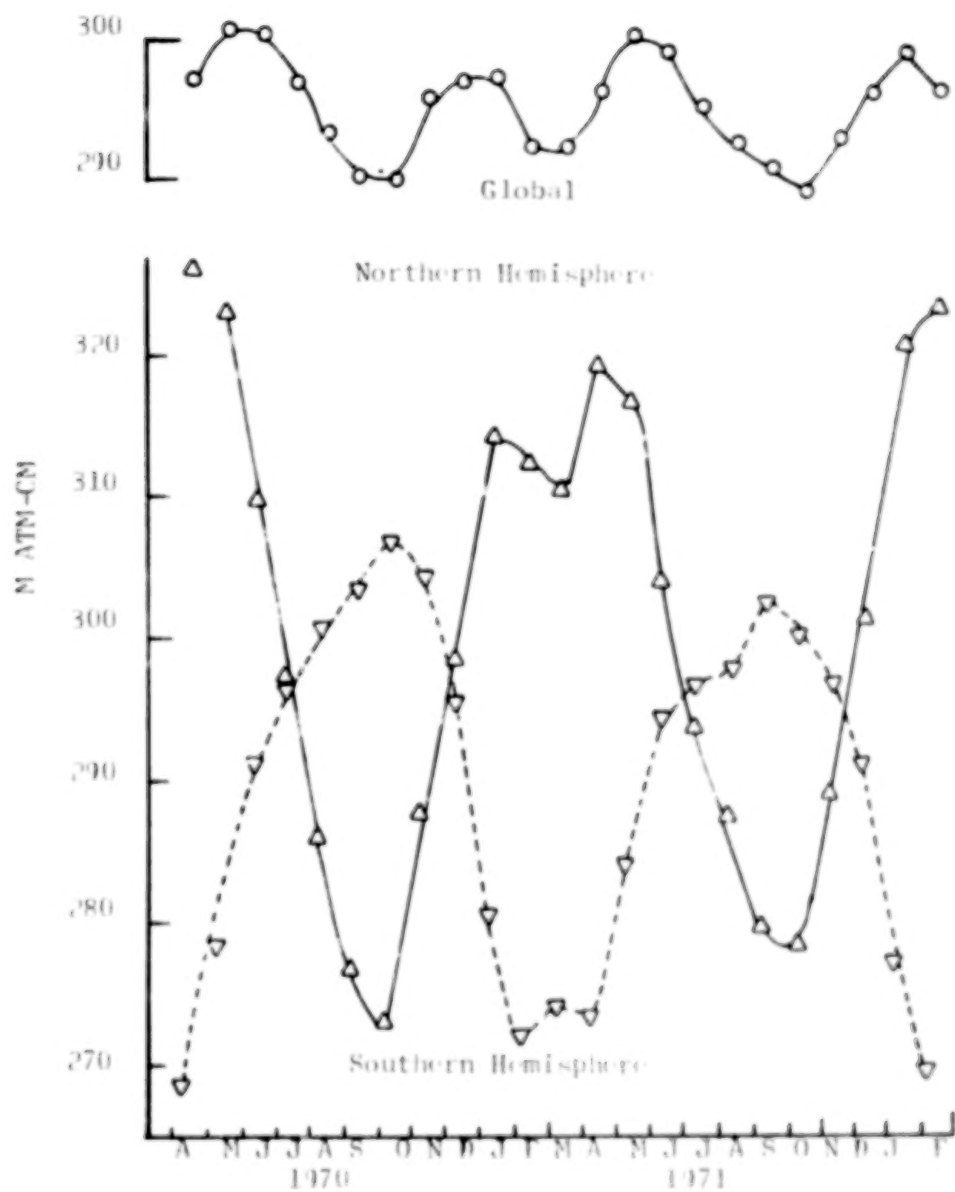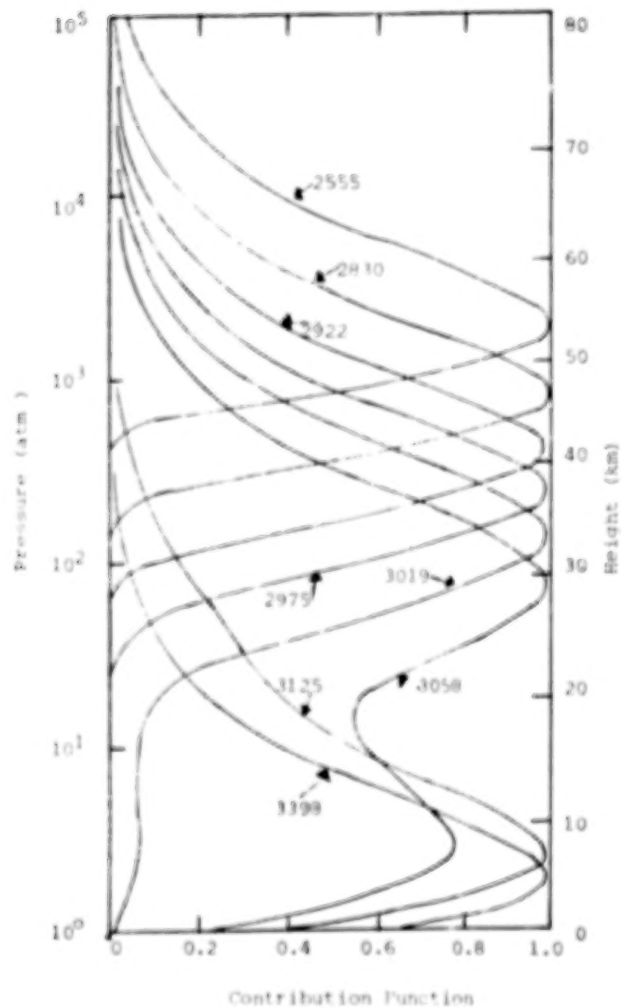
Figure 15.   Ozone Monthly Mean

Figure 16. Effective Scattering Levels for Solar
Radiation Scattered in the Nadir Direction of the
Satellite for all Orders of Scattering (Solar
zenith angle = 60°; Total ozone = 336 m atm-cm)
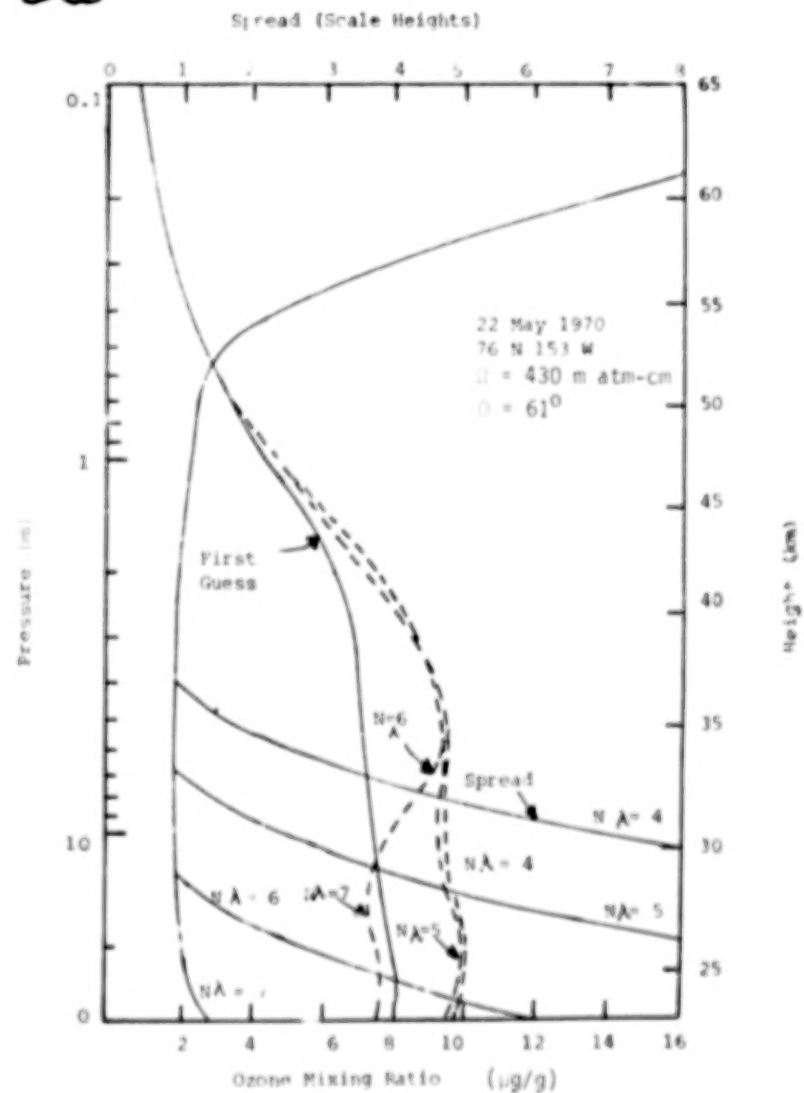
Figure 17. Balloon and Rocket Data

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PAGE

Figures 18 and 19 display two data sets from satellite observations. The massive solar proton event of August 4, 1972, is seen dramatically in a cavity in the ozone formed over the North Pole that persisted for at least two months. This same effect was not observed in the southern hemisphere, probably because it was winter and the ozone variability was very high.

Heath concluded that NASA's primary interest is in the stable high altitude observations where any effect of CFMs should show up. Figure 20 shows NASA's March 1977 assessment of the percent change in ozone due to CFMs.

Figure 18. Geodetic Zonal Means (80° N)

Figure 19.   Geodetic Zonal Means (0^0)

Figure 20.   Depletion of Ozone due to CFMs,   NASA
Assessment, March   1977

John Gille briefly described his Limb Radiance Infrared
Radiometer (LRIR) results with a special note on the difference
between accuracy and precision. The LRIR receives radiation
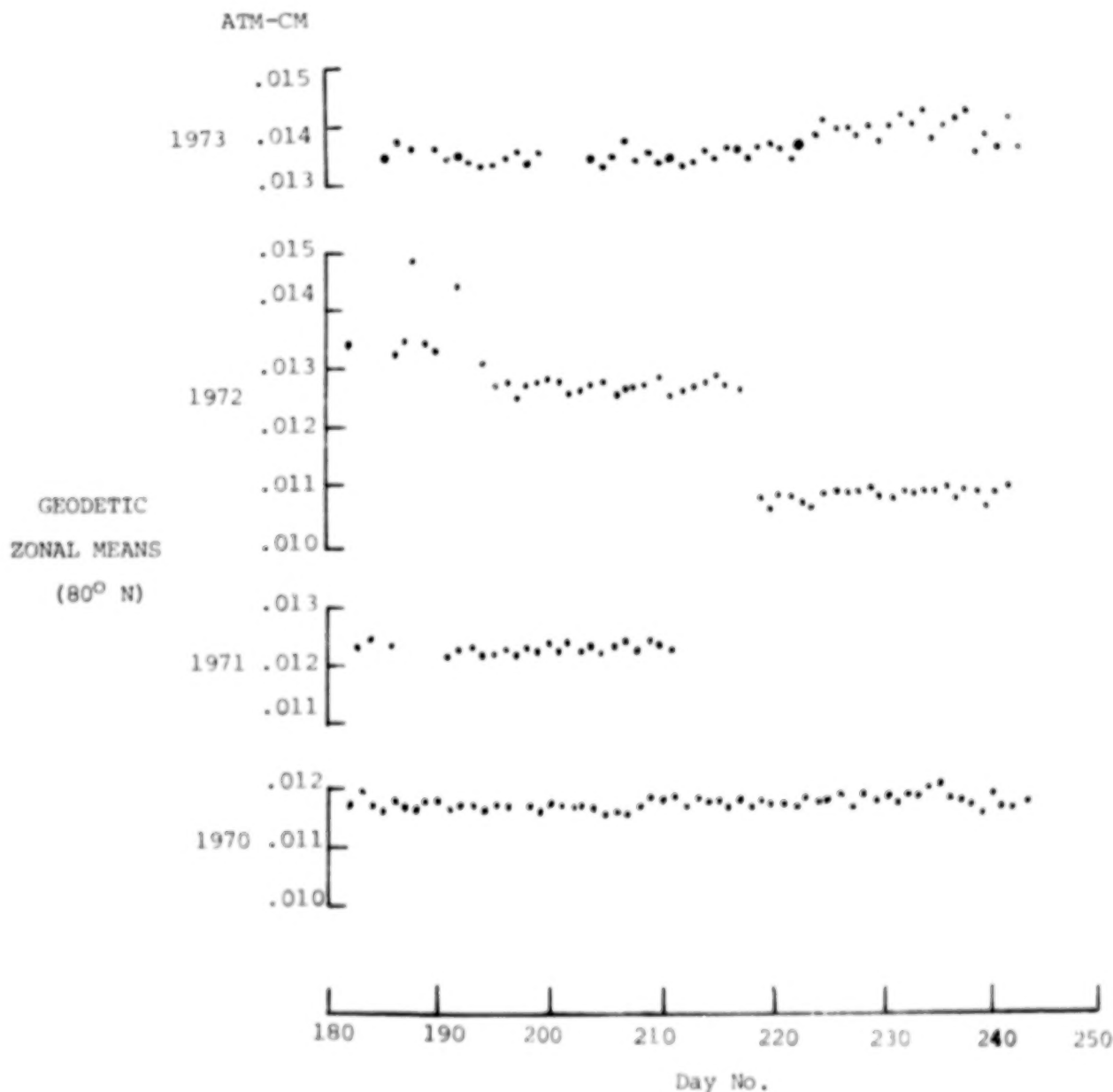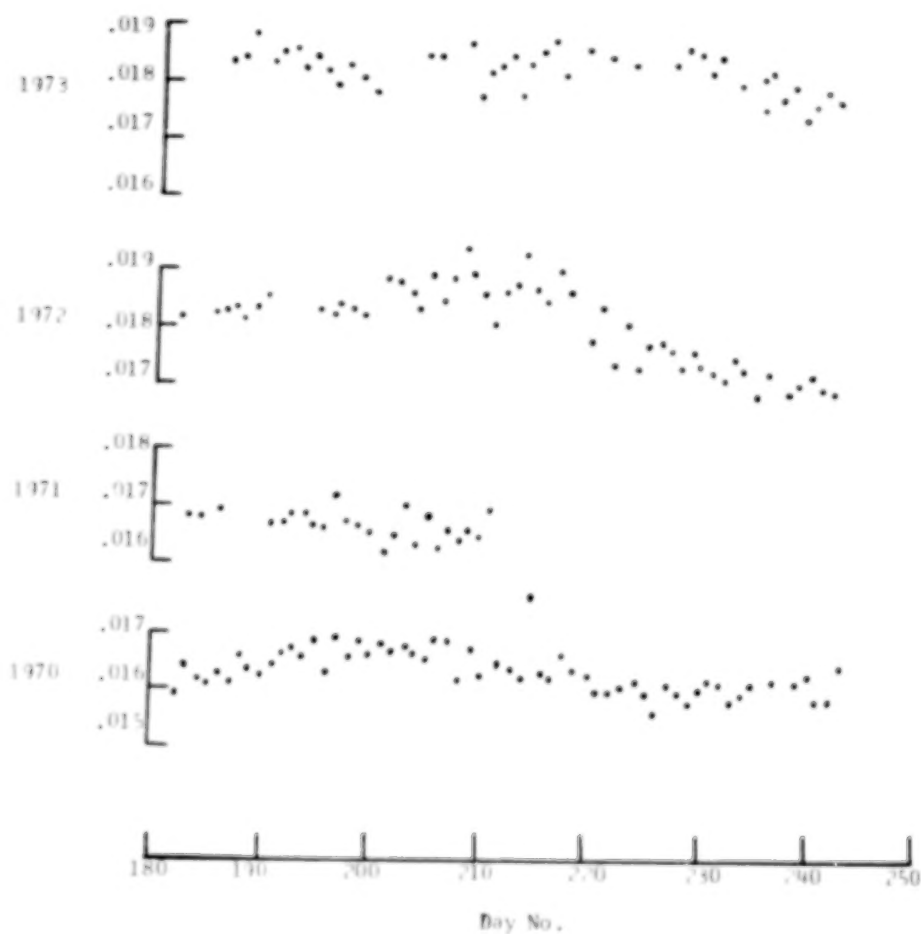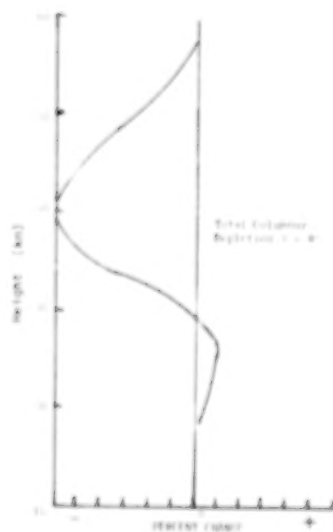from a 200- to 300-km-long path through the atmosphere. Cold
space behind the earth's limb eliminates any problems with back-
ground radiation and the ray path eliminates interference from
any lower atmospheric regions. The LRIR produces vertical ozone
distributions from 15 to 55 kms, as well as temperature distributions
(15 to 70 km). Water vapor profiles are expected in the future.

Gille stated that the LRIR accuracy is comparable to that of
other instruments including the optical rocketsonde, the chemi-
luminescent sonde, and the balloon ozonesonde. As to precision,
he noted that the LRIR instrument could get a reading every 25 km
or 12 to 15 profiles every 4° of latitude. The standard deviation
for a single profile is a function of altitude, but ranges from
about 1% at 30 km to 3% at 40 km and 10% at 48 km. He noted that
comparisons between LRIR and Limb Infrared Monitor of the
Stratosphere (LIMS), to be launched in 1978, would provide a very
sensitive test of variations at 40 km. For accuracy, he noted
that the rms agreement with the chemiluminescent rocketsonde
was 10%, about the stated accuracy of the rocket measurement.

James Lovill described the Air Force defense meteorological
polar orbiting satellite which can send 68,400 observations a day
to the Satellite Ozone Analysis Center (SOAC). Twenty-three
Dobson stations in 13 countries have agreed to provide special
ground truth measurements to the SOAC to use with the satellite data.

Detailing the measurement procedure, Lovill explained the
instrument, its flow diagram, some specific instrument parameters,
and the sensor scan geometry (Fig. 21). He then presented satel-
lite readings (Fig. 22), contoured them over the globe (Fig. 23),
and provided Arosa readings for July 1977 (Fig. 24) as an example
of the ground truth measurements. He concluded his presentation
with a display of correlation coefficients vs. distance for two
sets of total ozone stations (Figs. 25 and 26).
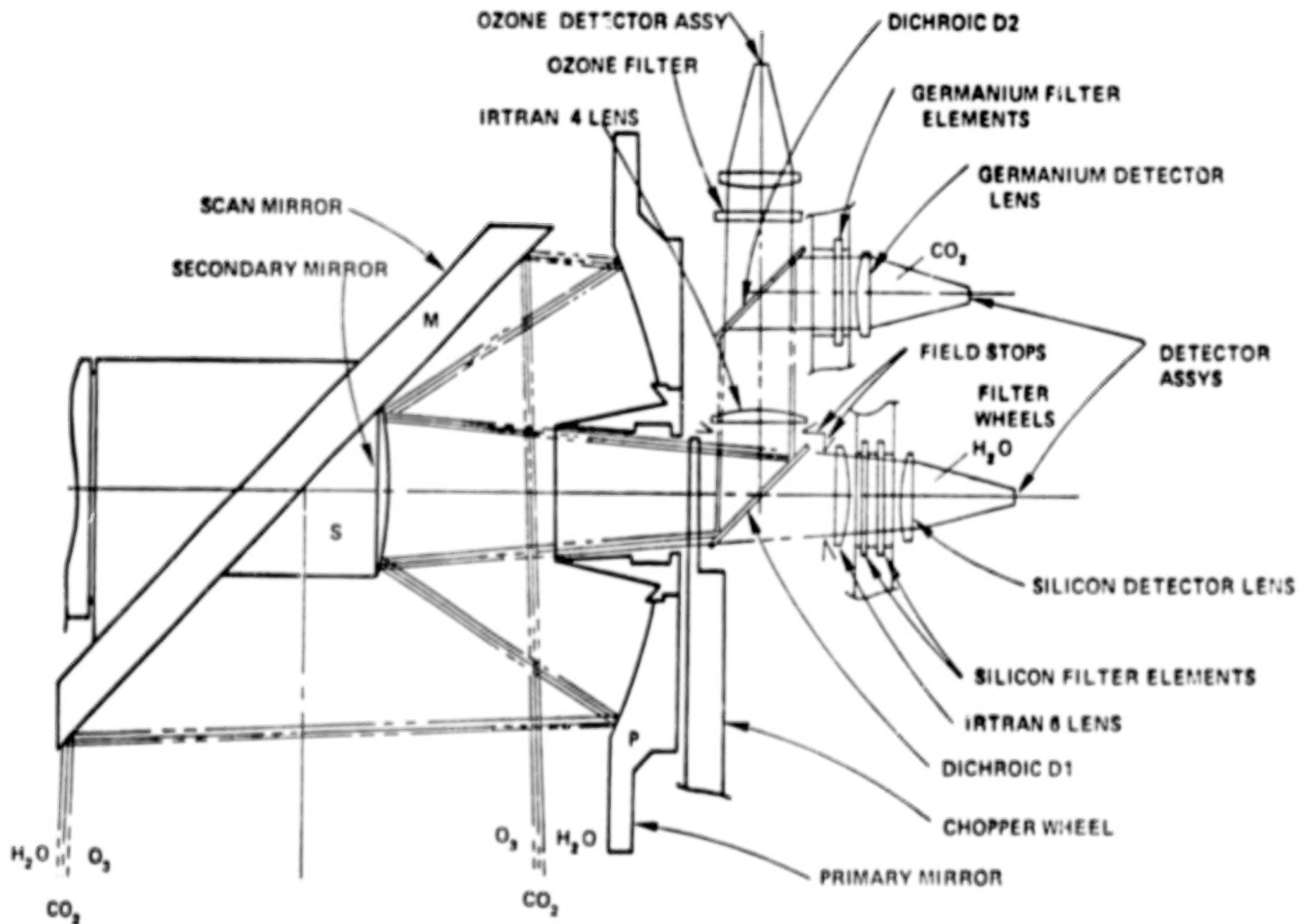
Figure 21. Optical Schematic of Ozone, Temperature and Water Vapor Sensor

April 19, 1969

	170W	150W	130W	110W	90W	70W	50W	30W	10W	10E	30E	50E	70E	90E	110E	130E	150E	170E	MEAN
70N	460	479	410	398	440	427	430	434	431	443	452	449	451	449	428	435	429	378	434
50N	397	413	352	367	420	351	389	400	371	403	422	399	384	361	334	370	390	349	381
30N	312	325	319	334	362	315	362	352	306	325	317	299	300	248	297	314	330	333	319
10N	252	254	256	251	265	257	317	290	263	267	251	265	260	241	265	267	307	295	267
10S	245	242	239	236	237	237	296	273	259	255	238	260	261	260	249	268	289	261	255
30S	280	283	288	300	286	288	307	289	289	291	274	281	289	268	279	303	282	202	208
50S	333	334	326	327	322	351	320	290	333	350	349	364	350	362	338	316	324	345	335
70S	383	371	338	340	362	390	362	347	369	379	375	411	436	369	362	329	362	390	370

Figure 22. Satellite Readings

Figure 23.   Satellite Readings Contoured Over the Globe

JULY 1977   AROSA, SWITZERLAND

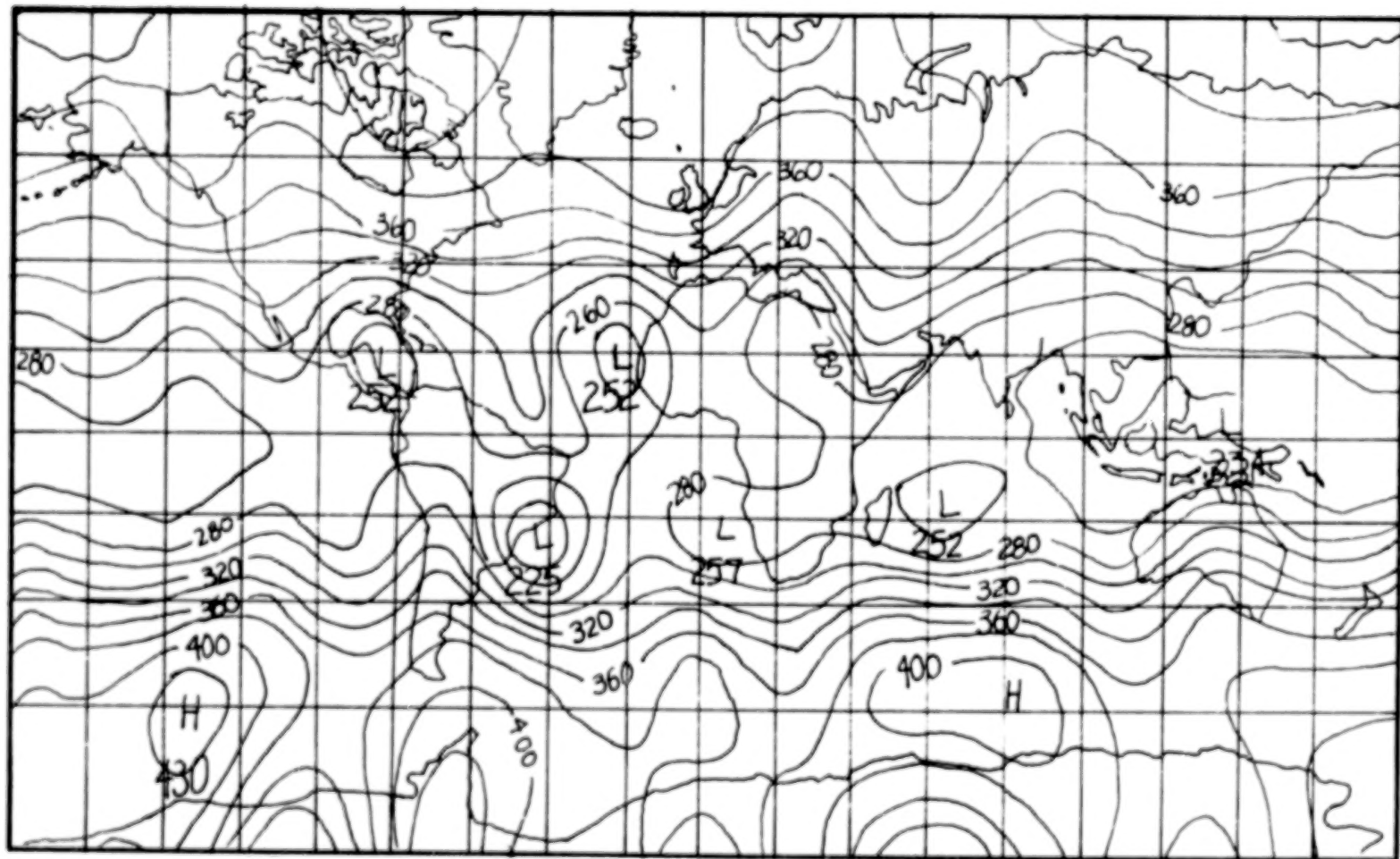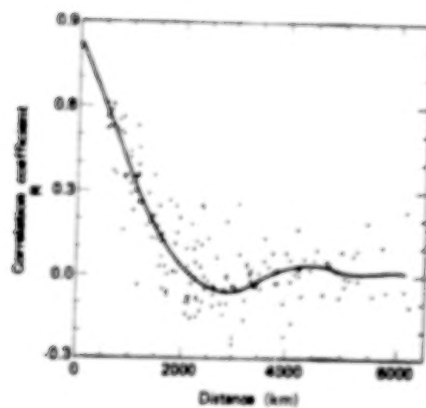|	D 15						GMT + 1h	D 101					
Day	TIME	I_θ	C	TIME	I_θ	AD		TIME	I_θ	C	TIME	I_θ	AD
11	7 46 30	4	351	7 47 30	4	345		7 48 30	4	340	7 50 30	4	347
	8 54 30	4	341	8 55 30	4	340		8 57 30	4	334	8 58 30	4	339
	10 24 30	4	345	10 25 30	4	342		10 27 30	4	333	10 28 30	4	344
	11 28	4	344	11 28 45	4	335		-	-	-	-	-	-
	11 30	4	343	11 30 45	4	336		11 32	4	329	11 32 45	4	337
	13 29	3-4	336	13 29 45	3-4	332		11 34	4	328	11 34 45	4	341
								13 31	3-4	327	13 35 15	3-4	339
12	7 04 30	4	303	7 05 30	4	302		7 07 30	4	292	7 08 30	4	299
	7 24 30	4	305	7 25 30	4	301		7 27 30	4	292	7 28 30	4	301
	7 47 30	4	304	7 48 30	4	304		7 50 30	4	295	7 51 30	4	303
	9 55 30	4	305	9 56 30	4	301		9 58 30	4	290	9 59 30	4	303
	11 10	4	301	11 10 45	4	301		11 14	4	290	11 14 45	4	303
	11 12	4	301	11 12 45	4	301		11 16	4	291	11 16 45	4	301
	11 51 30	4	305	11 52 30	4	300		11 54 30	4	292	11 55 30	4	301
	12 59 30	4	311	13 00 30	4	300		13 02 30	4	295	11 03 30	4	301
13	10 06 30	4	346	10 07 30	4	335		10 09 30	4	335	10 10 30	4	335
	11 10	3-4	345	11 10 45	3-4	333		11 12	3-4	333	11 12 45	3-4	334
14	8 27 30	3	336	-	-	-		8 25 30	3-4	328	8 26 30	3-4	329
	13 11	3	335	13 11 45	3	343		-	-	-	-	-	-
								13 13	3	341	13 14 45	3	344
								14 33	2-3	335	-	-	-
15	12 17	2-3	338	12 17 45	2-3	340		-	-	-	-	-	-
	12 55	3	345	12 55 45	3	345		12 55	3	337	12 55 45	3	343
	16 04	3	332	-	-	-		17 11	3	322	17 12 30	3	329
16	7 06 30	-4	327	7 07 30	-4	323		7 09 30	-4	317	7 10 30	-4	323
	7 25 30	4	331	7 26 30	4	326		7 25 30	4	319	7 26 30	4	325
	7 49 30	4	332	7 50 30	4	327		7 52 30	4	320	7 53 30	4	327
	9 32 30	4	341	9 33 45	4	333		9 36 30	4	328	9 37 30	4	344
	10 37	3-4	340	-	-	-		10 31 30	3-4	335	10 32 30	3-4	345
	11 43	4	344	11 43 45	4	338		-	-	-	-	-	-
	12 51 30	3-4	353	12 52 15	3-4	345		12 58	4	335	12 58 45	4	350
17	12 30 30	2-3	73.8	-	-	-		-	-	-	-	-	-

Figure 24.   Arosa Readings for July 1977

Figure 25. North American Total Ozone Stations
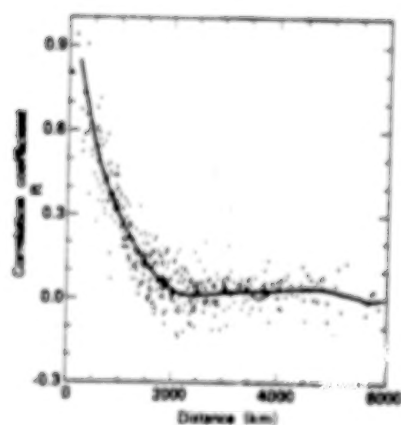(Data Period: 1960-1975)

Figure 26. European Total Ozone Stations
(Data Period: 1960-1975)

SESSION II: ESTIMATION OF TRENDS

William Hill, a statistical scientist, began his presentation with an illustration of ozone depletion curves predicted by the findings of the NAS (Fig. 27). In curve A, CFMs are assumed to be released at 1973 rates until some point in time where it is assumed that the releases are suddenly halted. The theory underlying curve A suggests that even after the release of CFMs is ended, a reduction in ozone will continue for approximately 10 additional years before the ozone gradually begins to return to its previous level.

Curve B illustrates the predicted depletion where it is assumed that CFMs are released at 1973 rates without interruption. By varying the rate constraints underlying the chemical reactions involved in the ozone destruction mechanism, a family of curves similar to A and B is produced.
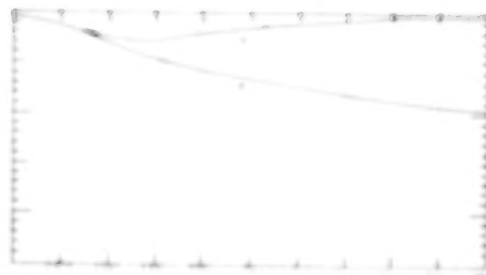

Figure 27. Ozone Depletion Curves

The application of statistical methods to recorded ozone measurements has an important role in the evaluation of the effect of human-related activities on the environment. Since the effects of a long-term depletion of ozone at magnitudes predicted by the NAS would probably be harmful to most forms of life, it is important to determine whether the leading edge of the hypothesized decline has occurred. Seeking to let the data speak for themselves, Hill created empirical pre-whitening filters the derivation of which was independent of the underlying physical mechanisms. When the data themselves are in question, statistical analysis can perform a "checks and balances" effort. Hill noted that time series modeling has some distinct advantages. It filters variations into systematic and random parts, errors are uncorrelated, and significant phase lag dependencies are identified. Hill discussed using time series modeling to enhance the capability of detecting trends.

Hill presented an analysis of ozone data using time series intervention analysis to determine whether the predicted decline has occurred in ozone. He first examined existing ozone data to determine whether a significant global abnormal trend--any positive or negative trend, man-made or natural, which cannot be explained by past ozone data records--has occurred as predicted in the ozone level in the 1970s. The second objective of Hill's analysis was to quantify the potential detectability that could be provided by future

monitoring of ozone concentrations through a global network of recording stations. Detectability refers to the smallest abnormal trend that would have to occur in the ozone measurements to be judged significantly different from zero trend. Early warning of a trend followed by correction of the cause would lead to the return to normal ozone levels (Fig. 28).

Hill presented plots of monthly total ozone values recorded at three sites: Tateno, Japan (36N, 140E), Mauna Loa, Hawaii (20N, 156W), and Aspendale, Australia (38S, 145E) (Fig. 29). Many characteristics of total ozone data are illustrated in these plots. The mean ozone levels increase as the distance from the equator increases. The amplitude of the seasonal variation exhibits a similar latitudinal dependency. Figure 29 also illustrates the phase difference in the ozone peaks between North Temperate and South Temperate Zone stations. One predominant characteristic of ozone data which is not obvious from this illustration is the strong seasonal and latitudinal dependency of the month-to-month variance of ozone concentrations.

Since ozone recording stations are not uniformly distributed around the globe, the close proximity of many of the stations casts doubt on the independence of the data records. Thus Hill selected a representative global sample of stations for analysis, a sample in which no particular region has a larger influence than any other region, by dividing the globe into nine equal areas (dark lines in Fig. 30) such that each area contains at least one active recording site with at least 10 years of continuous data. One station with no more than two missing values was chosen for analysis in each area. All data were recorded using the same type of instrument, and missing values were estimated by a graphical linear interpolation procedure.
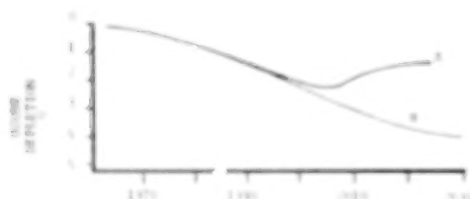

Figure 28. Hypothesized Ozone Depletion Profiles. Profile A: CFMs released at constant rate until some point in time at which all emissions are assumed to be curtailed. Profile B; CFMs released at constant rate without interruption.
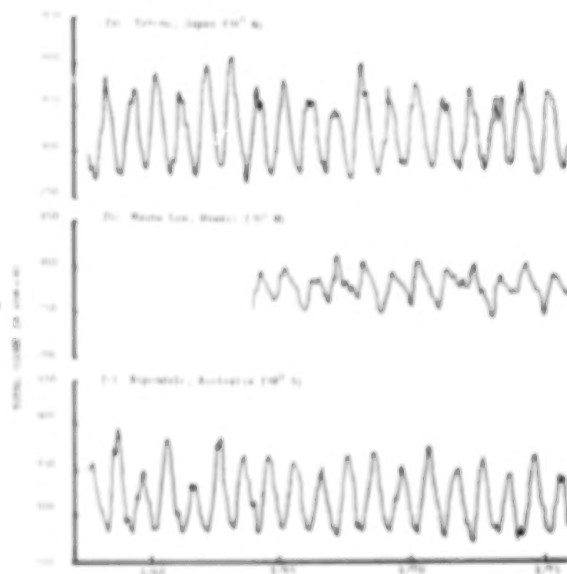

Figure 29. Mean Monthly Total Ozone Measurements Representative of the North Temperate (a), Tropical (b), and South Temperate (c) Data

The stations chosen for analysis using the above criteria are listed in Table 1 and are indicated by the large dots in Figure 30. Since ozone measurements were not made at Kodaikanal in May and June 1975, Hill truncated the series at April 1975. Other missing values occur prior to the period of hypothesized trends, and estimates of these missing values would be expected to have a small effect, if any, on the results.

Hill noted that while the global sample of stations was not truly a random sample of ozone recording sites, the restrictions did not compromise the results of the analysis.
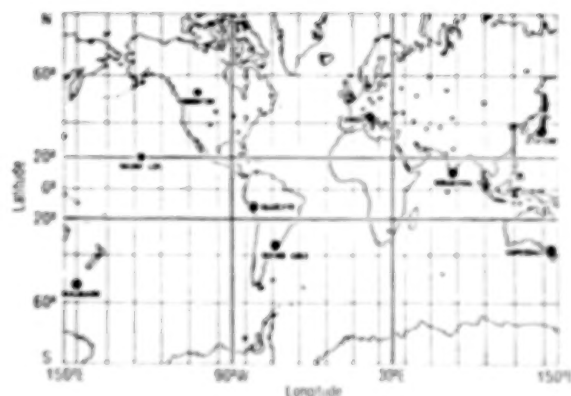
Figure 30. Stations Selected for Global Analysis of Total Ozone Data

Table 1. Stations selected for global analysis of total ozone data.

ZONE	STATION	LOCATION	PERIOD	MEAN LEVEL	# OF MISSING VALUES
North Temp.	Edmonton	54N, 114W	7/57-12/75	357	0
	Arosa	47N, 10E	1/57-12/75	333	2
	Tateno	36N, 140E	7/57-12/75	323	0
Tropics	Mauna Lca	20N, 156W	1/64-12/75	277	0
	Huancayo	12S, 75W	2/64-12/75	264	1
	Kodaikanal	10N, 77E	1/61-4/75	261	0
South Temp.	MacQuarie Isl.	54S, 159E	3/63-12/75	340	0
	Buenos Aires	35S, 58W	10/65-12/75	288	0
	Aspendale	38S, 145E	7/57-12/75	320	0

The ozone change, or trend, analysis is an application of the intervention analysis technique described by G.E.P. Box and G. C. Tiao in the Journal of the American Statistical Association in 1975. Intervention refers to the occurrence of a phenomenon (man-related or natural) which could possibly affect the level of a time series of data.

Hill's intervention analysis of ozone data attempts to determine whether a change exists in each of nine univariate series that would support the theory of a hypothesized depletion in ozone due to CFMs and other ozone depletion sources. Although the analysis can be completed in one step, Hill broke it into two steps so that the changing month-to-month variance of the ozone data can be more easily incorporated into the analysis.

In this analysis, time series models are first identified. One of the main reasons small trends can be detected is that there is a variance reduction capability in time series modeling. Tukey noted that Hill's "major output is standard errors because that will be most useful in trend detection." This is graphically illustrated (Fig. 31) using the monthly ozone data from Tateno, Japan.

RESULTING TATENO TIME SERIES MODEL

$$Y_t = \frac{(1 - \theta_{12} B^{12}) A_t}{(1 - \phi_1 B - \phi_2 B^2)(1 - B^{12})} = [FILTER] \times [ERROR]$$

where

Y_t = total ozone observed in month t

A_t = random uncorrelated noise (error) in month t

B = backshift operator such that $B^{12}Y_t = Y_{t-12}$

ϕ_1, ϕ_2 = autoregressive parameters representing dependencies between ozone values 1 and 2 months apart, respectively

θ_{12} = seasonal moving average parameter

rewritten

$$Y_t = Y_{t-12} + \phi_1 (Y_{t-1} - Y_{t-13}) + \phi_2 (Y_{t-2} - Y_{t-14})$$

$$-\theta_{12} A_{t-12} + A_t$$

(a) Original Data
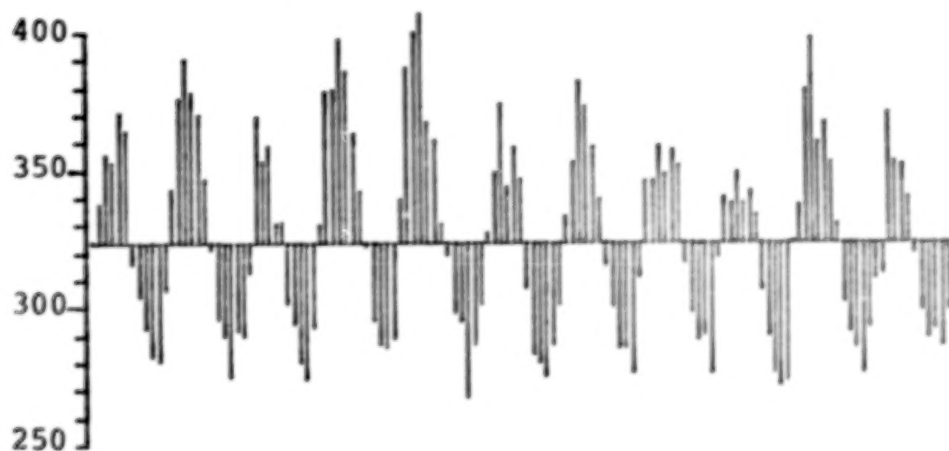
(b) Annual Cycle Removed - Original Variance Reduced by 68%

(c) Other Systematic Effects Removed - Original Variance Reduced by 87%

Figure 31.   Removing the Systematic Variation at Tateno
by Time Series Analysis

Removing the seasonal or annual cycle by using 12-month differences, the variance is reduced by 68% (Fig. 31b). By further identifyi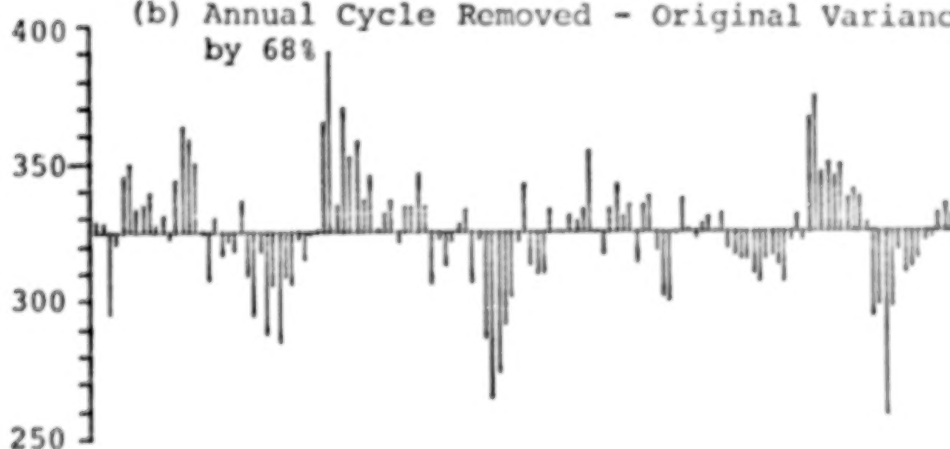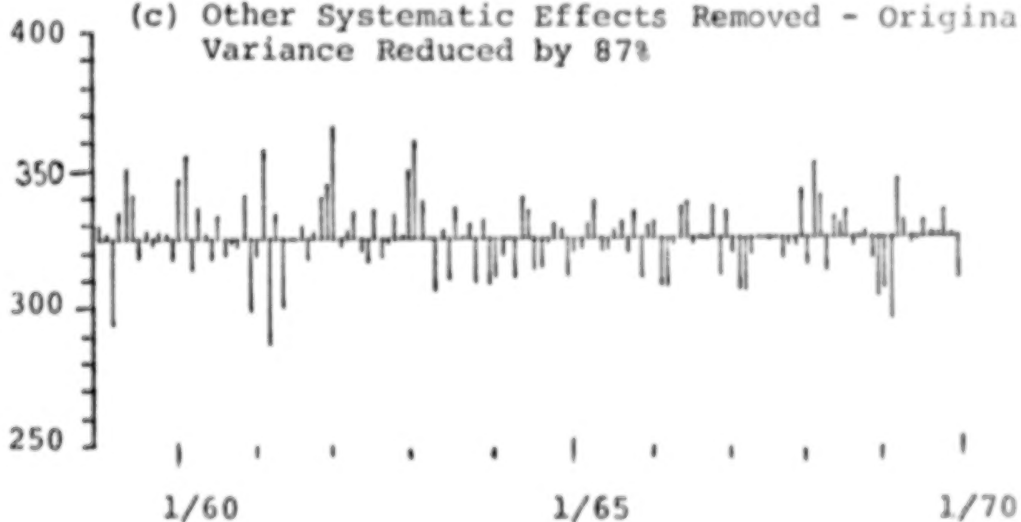ng and removing the significant dependencies that are still remaining (Fig. 31c), the original variance is reduced by a total of 87%. The eventual residual variation is characteristic of random error and has been checked for randomness by tests of significance.

To identify models for Tateno and the other stations such that the data are reduced to random error (a_t), the autocorrelation function which represents the correlations between data (e.g., deseasonalized data) separated by 1, 2, ..., k months is constructed and is examined for meaningful patterns. For Tateno, the auto-correlation function for the deseasonalized data (Fig. 32) is typical of a second order autoregressive model with a seasonal moving average term. When such a model is postulated and the corresponding coefficients estimated (see model in Table 2), Hill obtains the estimated residuals or errors (a_t) shown in Figure 33. Each model was arrived at independently. Discussion at this point included a comment by John Tukey that "nobody can look at an autocorrelation function and tell what's happening."
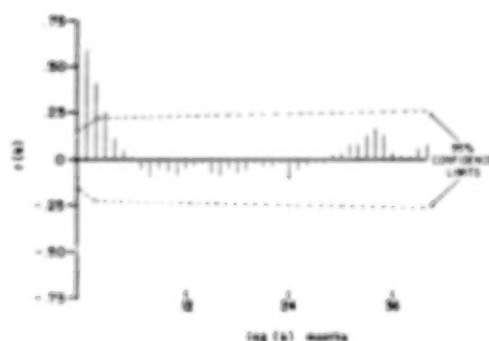
Figure 32. Autocorrelation Function of "Deseasonalized" Tateno Data 7/57-12/69

Hill reiterated that he is letting the data decide what is significant. Elmar Reiter countered that the "periodicity of the atmosphere varies too much to do this" and further proposed that eigen-values be calculated for as many stations as possible.

As a check of the independency of the residuals, the residual autocorrelation function which shows no unusual correlations or patterns is generated (Fig. 34). This supports the adequacy of the model and reaffirms the result that the data have had their systematic variation removed, leaving only the random part for estimating the background variance (σ^2) in trend detection calculations.

Hill identified the pre-intervention time series models and estimated parameters for each station using the Box-Jenkins Univariate Time Series computer package developed by D. J. Pack at Ohio State University. This package uses an unweighted non-linear least squares algorithm to estimate the ϕs and θs.

Table 2. Fitted time series models.
          Case 1: Identification and fit using data through 12/69
          Case 2: Identification and fit using data through 12/71
          Case 3: Identification and fit using data through end
                   of series

STATION	CASE	
Edmonton	1	$(1-.20B^1-.24B^2-.08B^3) (1-B^{12})y_t = (1-.65B^{12})a_t$
	2	$(1-.22B^1-.21B^2-.08B^3) (1-B^{12})y_t = (1-.66B^{12})a_t$
	3	$(1-.19B^1-.20B^2-.06B^3) (1-B^{12})y_t = (1-.69B^{12})a_t$
Arosa	1	$(1-.82B^1) (1-B^{12})y_t = (1-.66B^1) (1-.77B^{12}) (1+.17B^{11})a_t$
	2	$(1-.82B^1) (1-B^{12})y_t = (1-.65B^1) (1-.79B^{12}) (1+.24B^{25})a_t$
	3	$(1-.81B^1) (1-B^{12})y_t = (1-.65B^1) (1-.80B^{12}) (1+.26B^{25})a_t$
Tateno	1	$(1-.50B^1-.13B^2) (1-B^{12})y_t = (1-.76B^{12})a_t$
	2	$(1-.48B^1-.14B^2) (1-B^{12})y_t = (1-.77B^{12})a_t$
	3	$(1-.45B^1-.13B^2) (1-B^{12})y_t = (1-.81B^{12})a_t$
Mauna Loa	1	$(1-.65B^1) (1-B^{12})y_t = (1-.79B^{12})a_t$
	2	$(1-.62B^1) (1-B^{12})y_t = (1-.74B^{12})a_t$
	3	$(1-.64B^1) (1-B^{12})y_t = (1-.82B^{12})a_t$
Huancayo	1	$(1-.73B^1+.22 B^2-.27B^3+.17B^4-.34B^5+.18 B^6) (1-B^{12})y_t = (1-.73B^{12})a_t$
	2	$(1-.57B^1+.003B^2-.04B^3-.08B^4-.16B^5+.10 B^6) (1-B^{12})y_t = (1-.71B^{12})a_t$
	3	$(1-.49B^1-.02 B^2-.09B^3-.17B^4-.03B^5+.0003B^6) (1-B^{12})y_t = (1-.85B^{12})a_t$
Kodaikanal	1	$(1-.72B^1-.17B^2) (1-B^{12})y_t = (1-.62B^{12})a_t$
	2	$(1-.64B^1-.24B^2) (1-B^{12})y_t = (1-.67B^{12})a_t$
	3	$(1-.63B^1-.25B^2) (1-B^{12})y_t = (1-.70B^{12})a_t$
Buenos Aires	1	$(1-.56B^1+.16B^2-.17B^3) (1-B^{12})y_t = (1-.66B^{12})a_t$
	2	$(1-.48B^1+.13B^2-.24B^3) (1-B^{12})y_t = (1-.60B^{12})a_t$
	3	$(1-.40B^1+.03B^2-.19B^3) (1-B^{12})y_t = (1-.65B^{12})a_t$
MacQuarie Isles	1	$(1-.55B^1) (1-B^{12})y_t = (1-.73B^{12})a_t$
	2	$(1-.53B^1) (1-B^{12})y_t = (1-.68B^{12})a_t$
	3	$(1-.46B^1) (1-B^{12})y_t = (1-.75B^{12})a_t$
Aspendale	1	$(1-.47B^1-.13B^2) (1+.17B^{16}) (1-B^{12})y_t = (1-.70B^{12})a_t$
	2	$(1-.47B^1-.13B^2) (1+.17B^{16}) (1-B^{12})y_t = (1-.72B^{12})a_t$
	3	$(1-.45B^1-.15B^2) (1+.17B^{16}) (1-B^{12})y_t = (1-.74B^{12})a_t$

Let y_t, $t = 1, \ldots, N$ be a set of N observations collected at equal time intervals. Using all data obtained prior to the (hypothesized) intervention, the first step of the analysis is to identify a time series model of the form

$$\phi(B) \, (1-B^{12}) \, y_t = \theta(B) a_t \quad t=1,2,\ldots,T-1 \tag{7}$$

for each station, where

y_t is the mean monthly total ozone measurements,

a_t is independently distributed
  $N(o,\sigma_i^2)$ random errors, $i=1,\ldots,12$ referring to the
  12 months

B is the backshift operator (i.e., $B^k y_t = y_{t-k}$)

$\theta(B)$ is the moving average transfer function,

$\phi(B)$ is the autoregressive transfer function,

T is the time of hypothesized intervention, and

$(1-B^{12})$ is used to remove the seasonal variation of the
  monthly observations.

After obtaining estimates $\hat{\theta}(B)$ and $\hat{\phi}(B)$ of $\theta(B)$ and $\phi(B)$ which account for the phase lag dependencies in the data, a linear ramp function is introduced into the model at the point of intervention as the second step in the analysis. The model is now expressed as

$$y_t = \{\omega/(1-B^{12})\} \, \xi_t + \frac{\hat{\theta}(B)}{\hat{\phi}(B)(1-B^{12})} \cdot a_t \quad t=1,2,\ldots,N \tag{8}$$

where
$$\xi_t = \begin{cases} 0 & t < T \\ 1 & t \geq T \end{cases}$$

and ω represents the yearly rate of abnormal change in ozone measured in (m atm cm) per year. Rewriting equation (7) as

$$z_{t'} = \omega \, x_{t'} + a_{t'} \, , \quad t' = -T+1, -T+2,\ldots,-1,0,1,\ldots,n \tag{9}$$

where $t' = t-T$
        $n = N - T$
        $z_{t'} = [\hat{\phi}(B) \, (1-B^{12})/\hat{\theta}(B)] \, y_{t'}$
        $x_{t'} = [\hat{\phi}(B)/\hat{\theta}(B)] \, \xi_{t'}$

ω can be easily estimated by linear least squares.

Figure 33. General Methodology

In these series where the variance is not constant from month to month, approximately unbiased but not necessarily minimum variance estimators should be gotten for the ϕs and θs. (The transformation procedure of Box and Cox was applied to the original data $[y_t]$ to see if some power or logarithm transformation of y_t led to constant variance in the transformed variable. No variance stabilizing transformation was found. However, this posed no real problem since the main objective was to find nearly unbiased estimators for the ϕs and θs which could be fixed when estimating ω in the next step.)

The results of the model identification and estimation are summarized in Table 2 for Case 1, Case 2 and Case 3. The latter
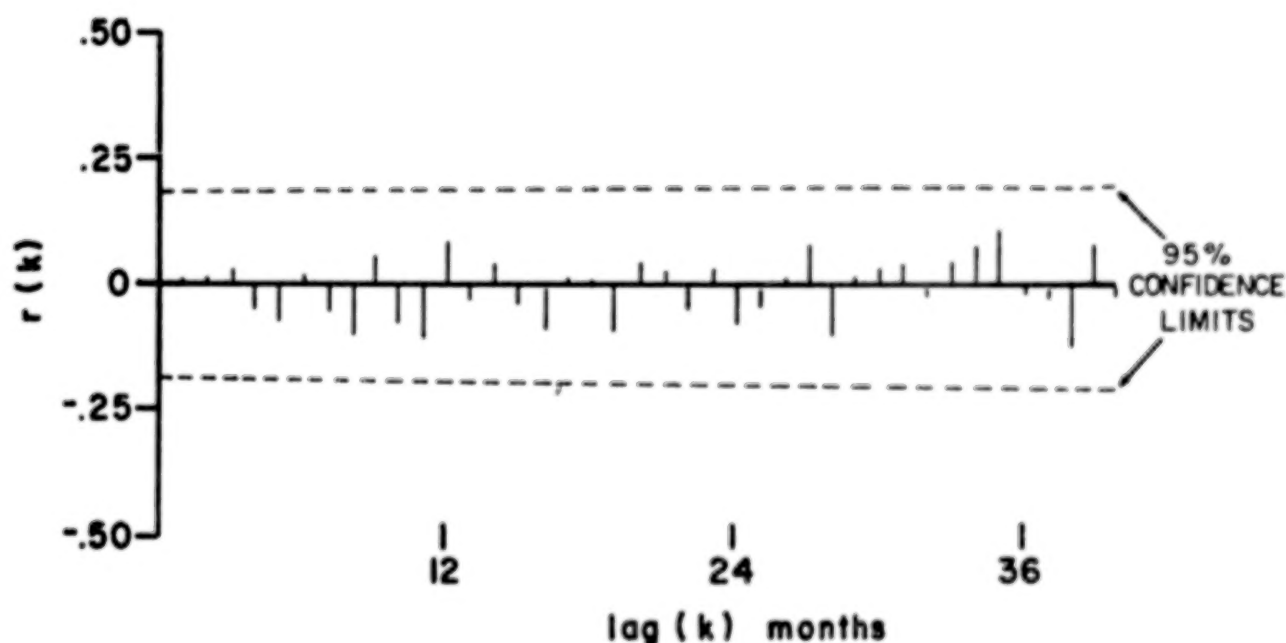

Figure 34. Autocorrelation Function of the Residuals
(Tateno Data 7/57-12/69)

is the fit for the complete series through 1975 which is needed
for later calculations. For each station the identification
program suggests the same model for both the shorter and longer
pre-intervention series (Case 1 vs. Case 2).

Once the time series models are thus identified and the para-
meters are estimated using nonlinear least squares and with data
first through 12/69 (Case 1) and then through 12/71 (Case 2), then
the ramp parameter ω is estimated from data beginning 1/70 to the
end of the series or from 1/72 to the end of the series. By proceeding
in this fashion the interval 1970-75 is examined for a possible
abnormal change due to intervention (as measured by ω) since it is
a period often associated with the predicted onset of man-made
ozone depletion. Each model is verified by applying tests of
significance to the residual autocorrelations. With the exception
of Huancayo, parameter estimates for Case 1 and Case 2 exhibit
only slight differences. (Negligible terms are left in the model
for Case 2 at Huancayo for comparison purposes only.) The results,
in general, suggest that the pre-intervention series are long
enough to allow for consistent model identification and estimation.
With regard to Huancayo, the relatively large change in parameter
estimates may be due to the near nonstationarity of the data
series as suggested by the large number of autoregressive terms
required to reduce the series to white noise. An instrument
drift is one possible explanation of the near nonstationary
behavior of the Huancayo series. Inspection of the identified
models gives some support for a suspected quasi-biennial cycle.
(See, for example, Arosa's moving average term of order 25.)

The results of the first step are the input to the second
step which involves estimating the abnormal trend parameter (ω)
for each series over the period of hypothesized change or inter-
vention. Estimates $\hat{\omega}$ of ω are obtained as the weighted least
squares solution to equation (9). Here the emphasis is
on obtaining not only an accurate or unbiased estimate for each ω
but also a precise estimate leading to improved sensitivity in trend
detection. Theoretically, weighted linear least squares will
give minimum variance unbiased estimators when there is non-
homogeneity of variance.

The weight assigned to each observation in the analysis is
the reciprocal of the standard deviation of all data for that
month prior to the hypothesized intervention. For example, in
Case 1, the weight for Tateno in May 1972 is the reciprocal of

the standard deviation for all May observations for Tateno prior
to 1970. By assigning weights in this manner, the weights are
not "contaminated" by observations which are potentially depleted.
Thus, defining

$$m = 1 + (\text{remainder } t'/12), \quad t' \geq 0$$

and w_1 = January "weight"

         w_2 = February "weight"

         etc.,

the $\hat{\omega}$ is obtained for each series and case as the least square
solution of

$$w_m z_{t'} = \omega \, w_m x_{t'} + w_m a_{t'}, \quad t' = 0,1,\ldots,n \tag{10}$$

where $z_{t'}$, $x_{t'}$, and t are as defined in equation (9). The standard
error of $\hat{\omega}$ is calculated for each station as

$$SE(\hat{\omega}) = \hat{\sigma}^2 (X'W^2 X)^{-1} \tag{11}$$

where   the elements of the vector X.

$$x_{t'} = \{\hat{\phi}(B)/\hat{\theta}(B)\} \xi_t, \quad t' = 0,1,\ldots,n$$

         (Note X' is the transpose of the vector X.)

         W is a diagonal matrix with w_m on the diagonal

and $\hat{\sigma}^2$ is an estimate of the weighted residual variance.

The estimates of ω and the standard errors are presented in
Table 3. For both cases, there are four positive estimates and
five negative values for ω covering the nine stations. In only
one instance, Huancayo (Case 2), is the estimate of ω different
from 0 at the 5% level of significance. The large difference
between $\hat{\omega}$ (Case 1) and $\hat{\omega}$ (Case 2) for Huancayo suggests that the
increase in the ozone level is a recent phenomenon and may be due
to nonenvironmental factors such as an instrument drift. Overall,
the results summarized in Table 3 suggest that, in the nine
stations analyzed, there has been neither a significant change
in the ozone level during the 1970s nor a positive or negative
tendency.

A global estimate of change in the ozone, $\hat{\omega}_G$, is obtained
by averaging the individual estimates of ω. To simplify the
calculation of the standard error of $\hat{\omega}_G$, the nine station residuals
were assumed to be independent of one another.

Table 3. Estimated values of ω and standard errors measured in (m atm-cm) per year.

STATION	CASE 1		CASE 2	
	$\hat{\omega}$	SE($\hat{\omega}$)	$\hat{\omega}$	SE($\hat{\omega}$)
Edmonton	+0.582	1.96	+0.727	2.56
Arosa	-0.407	1.10	-0.638	1.64
Tateno	+0.471	1.10	+0.185	1.56
Mauna Loa	-0.170	0.70	-0.400	0.99
Huancayo	+0.886	0.92	+2.330[1]	1.18
Kodaikanal	-2.220	2.10	-1.895	2.30
MacQuarie Isl.	+1.610	1.84	+3.710	2.70
Buenos Aires	-0.277	1.59	-0.434	2.45
Aspendale	-1.180	0.90	-1.167	1.25
Global Avg.	-0.078	0.48[2]	+0.269	0.65[2]

(1) Significantly different from 0 at 5% level of significance (2-sided).

(2) Pooled estimate.

Hill checked this assumption by studying the cross-correlation coefficients between the residuals for all 36 pairings of the nine series at different lead/lag values. If two stations are independent, the cross-correlation coefficients should have zero mean and show no pattern that clearly denotes a relationship. Hill detailed his tests of the data for independency.

Since not all the series are variance stationary and hence not likely jointly covariance stationary, the cross-correlation analysis is applied to the weighted residuals. It can be expected that the weighted residuals will be approximately white noise. For two

independent white noise series, the 95% confidence limits for the estimated cross-correlation coefficient for a lag of k months are approximately $+2 \times (N-|k|)^{-\frac{1}{2}}$. Figure 35 illustrates a typical cross-correlation function which was observed in the analysis.

A summary of the significant cross-correlations for the weighted residuals is given in Table 4 for up to lead/lag 12 months, a period Hill said is more likely to show a relationship between stations, if one exists.

There are 35 significant cross-correlations out of a total of 900 values, 25 lead/lag cross-correlation coefficients calculated for each of 36 pairings. The observed percentage of significant cross-correlations is therefore 4% as compared with the theoretical 5%, if each series is white noise. Although there are no obvious patterns in Table 4, certain of the significant cross-correlations might indicate either a chemical or physical transport phenomenon. For example, two pairings of tropical stations--Huancayo-Mauna Loa and

Figure 35. Estimated Cross-correlation Coefficients $\hat{r}_{12}(k)$ of Weighted Residuals from Arosa and Tateno Models (fit through 1975). A Positive Lag (k) Represents Tateno Lagging Arosa by k Months. The Dashed Lines are the Approximate 95% Confidence Limits.

Kodaikanal-Huancayo--show a positive cross-correlation between residuals of the same month (or lag 0). One of these, the largest cross-correlation coefficient to be estimated in this analysis, is 0.35 between Huancayo and Mauna Loa. Despite the fact that the significant cross-correlations are small in magnitude, these two pairings might be suggesting some relationship between tropical stations where the chemical effects related to ozone production dominate. There is a possibility that both chemical production and physical transport factors may explain these and some of the other significant lead/lag cross-correlations. Regardless, neither the pattern of the cross-correlations nor the proportion of significant values seems to contradict the general assumption of independency.

A further test of independency is obtained by applying the asymptotic approximation formula of Haugh

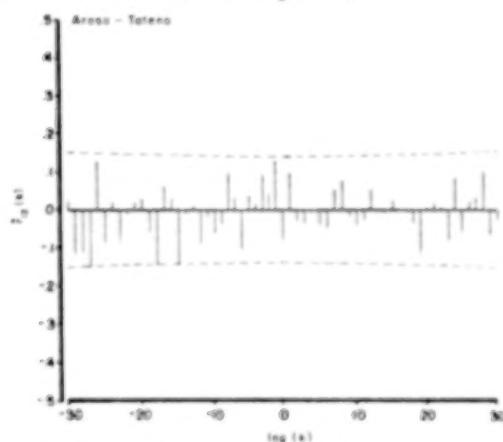$$S_M^* = N^2 \sum_{k=-M}^{M} (N-|k|)^{-1} \hat{r}_{12}(k)^2 \tag{12}$$

Table 4. Significant cross-correlation coefficients for weighted residuals. ($A \rightarrow B^+$ means B lags A by k months with a significant positive (+) correlation.)

Lead/Lag (k)	Significant Cross-Correlations
0	$Kod \rightarrow Hua^+$, $Hua \rightarrow Mau^+$, $Asp \rightarrow Mac^-$
1	$Edm \rightarrow Mau^-$, $Tat \rightarrow Asp^-$, $Bue \rightarrow Kod^-$, $Kod \rightarrow Edm^-$
2	
3	$Mac \rightarrow Edm^+$, $Tat \rightarrow Asp^+$, $Kod \rightarrow Asp^-$, $Mac \rightarrow Kod^+$, $Mau \rightarrow Kod^-$
4	$Mac \rightarrow Mau^-$
5	$Mau \rightarrow Tat^-$, $Mau \rightarrow Mac^-$, $Asp \rightarrow Bue^+$
6	$Bue \rightarrow Hua^-$, $Tat \rightarrow Asp^+$, $Mau \rightarrow Asp^+$, $Edm \rightarrow Aro^-$
7	$Hua \rightarrow Aro^-$, $Kod \rightarrow Aro^+$, $Kod \rightarrow Tat^-$
8	$Tat \rightarrow Kod^-$, $Bue \rightarrow Hua^+$, $Tat \rightarrow Asp^-$, $Asp \rightarrow Tat^-$
9	$Tat \rightarrow Mau^-$, $Tat \rightarrow Asp^+$
10	
11	$Bue \rightarrow Mau^+$, $Hua \rightarrow Mau^-$, $Aro \rightarrow Asp^-$
12	$Bue \rightarrow Mau^+$, $Kod \rightarrow Asp^-$, $Bue \rightarrow Kod^+$

where $\hat{r}_{12}$ is the estimated cross-correlation coefficient between series 1 and series 2 at lag(k), and M is set equal to 12. The test statistic S_M^* is compared to the χ^2 distribution with 2M+1 = 25 degrees of freedom. We would not reject series 1 and 2 as being independent if S_M^* is less than the χ^2 = 37.7 at the 5% significance level. Only four of the 36 pairings have a significant $S_M^* \geq 37.7$. These are Aspendale-Tateno, Buenos Aires-Mauna Loa, Huancayo-Mauna Loa, and Mauna Loa-Tateno. In the two latter pairings, a single cross-correlation dominates the estimate of S_M^*. There is the lag (0) positive cross-correlation between Huancayo and Mauna Loa, and the negative cross-correlation for Tateno lagging Mauna Loa by 5 months. The high S_M^* between Aspendale and Tateno is reflecting

the significant correlations at k = -9, -8, -6, -3, -1, 8 in Figure 36 and Table 4. (The negative k means Aspendale lags Tateno.) This may be reflecting some transport pattern of ozone between two stations which have nearly the same longitude and are approximately equal distance but opposite in direction from the equator. The Buenos Aires-Mauna Loa value for S_M^* is largely affected by the cross-correlations at lags 11 and 12 months (Table 4).

In summary, two types of statistical tests have been performed on the cross-correlations of the residuals from all 36 pairings of stations. The proportion of significant results does not appear unusual, nor does there appear to be a dominant pattern that would lead one to reject the net or general assumption of independency. There are, however, certain significant cross-correlation coefficients that could be reflecting ozone production characteristics in the tropics and

Figure 36. Estimated Cross-correlation Coefficients of Weighted Residuals from Aspendale and Tateno Models (fit through 1975). A Positive Lag (k) Represents Tateno Lagging Aspendale by k Months. The Dashed Lines are the Approximate 95% Confidence Limits.

ozone transport between regions. These cross-correlation coefficients are relatively small, and since they represent a reasonably balanced mix of positive and negative covariances, their additive effect on $SE(\hat{\omega}_G)$ is likely to be slight with $SE(\hat{\omega}_G)$ either being slightly larger or slightly smaller than already estimated.

Thus, an analysis of the cross-correlations of the residual series does not lead to a contradiction of the assumption that the nine station residuals are independent of one another. The individual estimates of the standard error of $\hat{\omega}_i$, $i = 1,...9$, are therefore combined to provide an estimate, $SE(\hat{\omega}_G)$, of the standard deviation of $\hat{\omega}_G$. That is:

$$SE(\hat{\omega}_G) = \left[(1/9)^2 \sum_{i=1}^{9} SE(\hat{\omega}_i)^2 \right]^{\frac{1}{2}} \tag{13}$$

By dividing $\hat{\omega}_G$ and $SE(\hat{\omega}_G)$ by 307, the overall ozone average can be obtained based on the sample of nine stations. To express this as a percent, the estimated abnormal global rate of change per year for Case 1 is -0.03% ± 0.31% (95% confidence limits). For Case 2, the estimate is 0.09% ± 0.42%. Both results suggest there has been no statistically significant change in global ozone persisting in the 1970's.
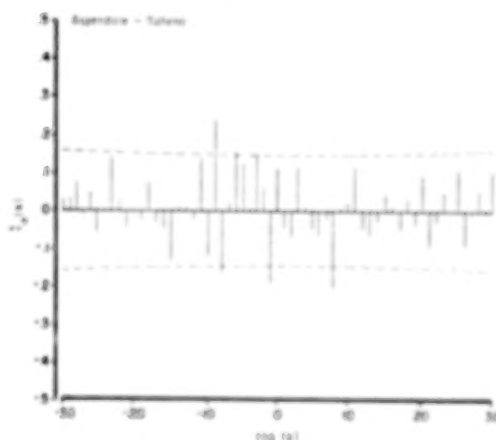
Setting out to check his linear ramp function with a simulation, Hill determined how well the methodology estimates a predicted decline if the decline were moderately exponential (Fig. 28) instead of linear. All ozone data are artificially reduced according to the ozone depletion model proposed by Jesson (Fig. 37). Using the pre-intervention models in Table 2, a new trend estimate, $\hat{\omega}'$ is calculated for each station after the data are artificially depleted and compared to the original. If the methodology is to be appropriate for ozone trend estimation, the differences $\hat{\omega}_i - \hat{\omega}_i'$, i=1, ...9, when expressed as a percentage of the mean level for station i, should be close to 0.11% for Case 1, where 0.11% is the average amount each data series is depleted per year in the intervention interval. For Case 2, the percent difference should be close to 0.13%. The results of the simulation, summarized in Table 5, indicate close agreement between the artificial exponential depletion and the estimate of depletion from the intervention

Figure 37. This Profile Represents an Earlier Estimate of Depletion Where the Effect of the Chemistry of Chlorine Nitrate is to Reduce the Depletion Predictions. The Predictions of Figure 37 should not be Compared with Those in Figure 28.

analysis. These results indicate that the use of the linear ramp function of equation (11) will serve as a good approximation to typical ozone depletion profiles in the 1970s. As a further check on the analysis, each data series was artificially depleted using a linear depletion model. The trend analysis estimated the reduction exactly, as would be expected from the underlying theory.

Pursuing the issue of global detectability afforded by the monitoring of ozone levels beyond 1975, Hill recalled that detectability is defined as the smallest abnormal change that would have to occur in the ozone data to be considered significantly different from zero change. Quantitatively, at the 95% confidence level, this is simply expressed as $1.96 \times SE(\hat{\omega}_G)$. This is converted to a percentage by dividing by 307, the global average of the nine stations and multiplying by 100%.

Since no abnormal trend is found in the period prior to 1975 (Figs. 38 and 39), the models are refitted over the complete data set (Case 3, Table 2). These show no inadequacies such that the identification step had to be redone. Special attention is paid to the ratio: (mean residual)/(standard error) at Huancayo. Since this is not significant, a trend term did not need to be included in the model.

Table 5. Simulation results for artificial depletion shown in
Figure 37, where $\hat{\omega}$ is the estimated trend parameter for the
original data, and $\hat{\omega}'$ is the estimated trend parameter for
the artificially depleted data.

$$\Delta\hat{\omega}(\%)=100\% \times (\hat{\omega}'-\hat{\omega})/(\text{average ozone level for the station})$$

STATION	CASE 1			CASE 2		
	$\hat{\omega}$	$\hat{\omega}'$	$\Delta\hat{\omega}(\%)$[1]	$\hat{\omega}$	$\hat{\omega}'$	$\Delta\hat{\omega}(\%)$[2]
Edmonton	+0.582	+0.108	-.13%	+0.727	+0.050	-.19%
Arosa	-0.407	-0.870	-.14	-0.638	-1.200	-.17
Tateno	+0.471	-0.054	-.16	+0.185	-0.400	-.18
Mauna Loa	-0.170	-0.539	-.13	-0.400	-0.914	-.19
Huancayo	+0.886	+0.578	-.18	+2.330	+1.950	-.14
Kodaikanal	-2.220	-2.420	-.08	-1.895	-2.150	-.10
MacQuarie Isl	+1.610	+1.230	-.11	+3.710	+3.080	-.16
Buenos Aires	-0.277	-0.627	-.12	-0.434	-0.812	-.13
Aspendale	-1.180	-1.510	-.10	-1.167	-1.660	-.15
Global Avg.	-0.078	-0.456	-.12%	+0.269	-0.228	-.16%

1 Compare with -.11%

2 Compare with -.13%

EVALUATING FOR TREND 1970 - 1975 AT TATENO

PRE 1970, MODEL IS

$$Y_t = \frac{(1 - \theta_{12} B^{12}) A_t}{(1 - \phi_1 B - \phi_2 B^2)(1 - B^{12})}$$

IF TREND 1970 - 75, THEN

$$Y_t = \frac{\omega}{(1 - B^{12})} \xi_t + \frac{(1 - \theta_{12} B^{12}) A_t}{(1 - \phi_1 B - \phi_2 B^2)(1 - B^{12})}$$

WHERE

$$\xi_t = \begin{cases} 0 & \text{BEFORE } 1/70 \\ \\ 1 & \text{FROM } 1/70 \end{cases}$$

QUESTION: IS ω SIGNIFICANTLY DIFFERENT FROM ZERO?

WHERE ω = ABNORMAL YEARLY RATE OF CHANGE IN TOTAL OZONE

Figure 38. Evaluating Trend at Tateno

TREND DETECTABILITY THRESHOLDS FOUND BY

(1) REFITTING MODELS THRU 1975 (SINCE NO PRIOR TREND)

(2) CALCULATE STANDARD ERROR (SE($\hat{\omega}$)) OF FUTURE $\hat{\omega}$

(3) CALCULATE STANDARD ERROR OF GLOBAL AVERAGE $\hat{\omega}_G$

$$SE(\hat{\omega}_G) = \left[(1/9)^2 \sum_{i=1}^{9} SE(\hat{\omega}_i)^2 \right]^{\frac{1}{2}}$$

IF 9 STATIONS INDEPENDENT

(4) CALCULATE THRESHOLD AT 95% CONFIDENCE

$$1.96 \times SE(\hat{\omega}_G)$$

CONVERT TO %

Figure 39. Finding Trend Detectability Thresholds

Prior to calculating $SE(\hat{\omega}_i)$ and hence $SE(\hat{\omega}_G)$ corresponding to an intervention starting at 1/76 and going into the future, consider each term of equation (11). The vector X is a function of the pre-1/76 data and the length of the intervention interval; W^2, the diagonal matrix of weights, is a function only of the preintervention data, and $\hat{\sigma}^2$ is the only term which depends on the post-intervention data. Assuming the residual variation prior to 1/76 has the same variance structure as after 1/76, then $\hat{\sigma}^2$ can be calculated as

$$\hat{\sigma}^2 = (T-1-(p+q))^{-1} \sum_{s=L+1}^{T-1} W_m^2 (y_s - \hat{y}_s)^2 \tag{14}$$

where T corresponds to 1/76, the point of intervention

   p is the number of autoregressive terms in the model

   q is the number of moving average terms in the model

   L is the maximum back order

and $\hat{y}_s$ is the one step ahead forecast made at time s-1 using
       models of the form in equation (7)

Estimates of detectability for future monitoring periods of 3 to 8 years are presented in Table 6. Column 2 of Table 6 presents detectability estimates based on the sample of the nine stations. The results indicate that an abnormal change of 0.26% per year, persisting for six years (1.56% total), would represent a significant change in the ozone level, if it were to occur. If the monitoring period extended for eight years, a persistent yearly rate of change of 0.21% per year (1.68% total) would be considered significant. Column 3 gives the detectability estimates based on a global network of recording locations equivalent to 18 independent uniformly-distributed sites with residual variation similar to the nine stations analyzed. This "18-station network" can be constructed by including more of the existing ground-based stations in the analysis and/or using satellite data which should be available shortly. Calculations indicate that an abnormal change close to 1% is detectable from the total ground-based network, if such a change were to occur. A combination of data prior to and after January 1976 (e.g., January 1974 - 78) should provide detectability close to the tabulated estimates.

Table 6. Yearly global ozone changes that must persist for p
years to be judged statistically significant.

NUMBER OF YEARS	9-STATION GLOBAL NETWORK	18-STATION GLOBAL NETWORK
3	.48%	.34%
4	.37	.26
5	.31	.22
6	.26	.19
7	.23	.16
8	.21	.15

One apparent characteristic of the intervention analysis
is that the total detectability lessens as the monitoring interval
lengthens. For example, based on the nine stations analyzed, a
total change of 1.44% corresponding to 0.48%/year for three years
would be significant, while the total change in eight years at
0.21%/year would have to be 1.68% before it could be judged
significant (see Table 6). Hill noted that, "intuitively, this
is what one might expect. The faster the yearly rate of change,
the smaller the total effect needs to be to be judged significant.
Very gradual rates of change are more difficult to detect leading
to longer elapsed times and greater total changes. A rigorous
interpretation lies in the error propagation characteristics of
the estimated step function $(\hat{\omega}/(1-B^{12}))\epsilon_t$ with increasing time."

Assuming that the predicted ozone depletion effects for the
various compounds are additive, the predicted net global effect
is in the range of 1-2% and should by now be large enough to have

produced a detectable change in the ozone level. The fact that
the trend analysis shows no significant abnormal change in ozone
suggests that, although the depletion theories may be correct,
the depletion predictions when treated cumulatively yield a result
that appears to be too large.

Hill concluded that, "The detectability analysis indicates
that the ozone data provide an excellent basis for future monitor-
ing of ozone concentrations. The effect of the early warning
provided by the data is to minimize the impact on the environment
of a change in the ozone level due to man-related activity, if
such a change were to occur. For example, if FC-11 and FC-12
were to cause a 1.56% depletion in the ozone in the next six
years, an estimated maximum depletion 1.5 times greater (factor
based on NAS calculations), or 2.3%, would occur and be followed
by a gradual reversal to normal, assuming that the cause is
identified and controlled. (See curve A, Fig. 28.) Thus,
attention could center upon climatic and biological impacts
resulting from potential maximum reversible changes of 2.3%.
Further calculations indicate that the detection capability can
be increased by incorporating additional ground station data
and/or satellite data into the monitoring scheme (Table 6,
column 3)."

Hill noted his assumptions that the cause or causes of an
ozone depletion can be identified and controlled. If future
monitoring should reveal a significant change in the ozone level,
careful investigation of all potential depletion sources, human-
related and natural, would be necessary before a cause could be
identified. For example, natural trends could be mistaken for man-
made effects if the periodicity of the natural trend is greater
than the ozone record. This would be true of some shorter data
series where cycles, such as a suspected 11-year cycle, may not be
fully identified and accounted for in the time series model. Trends
which might have been caused by instrument drift or local phenomena
can be verified by comparing the suspicious results with those of
neighboring stations for consistency. Thus, knowledge of both
chemical and physical processes associated with ozone activity
will be necessary to complete a cause-and-effect evaluation if
statistical analysis of ozone data reveals a significant change
in ozone concentration.

Next, Marcello Pagano, from the State University of New
York at Buffalo, presented his methodology for analyzing the
data by using the time series of ozone monthly means from the
same nine-station network (Table 7) that Hill used. Pagano re-
iterated that this network serves as a globally-balanced sample
of ozone monitoring stations whose time series had no missing

Table 7.   Time series of ozone monthly means.

Station and Dates of Observations	Model Method	Ratio of Before and After Mean Square Prediction Errors PRER			Proportion Negative Forecast Errors NEGER		
		24 mo.	48 mo.	72 mo.	24 mo.	48 mo.	72 mo.
AROSA Jan 58-Dec 75	2	1.47	1.26	1.28	.67	.65	.61
ASPENDALE Jan 58-Dec 75	2	.92	1.09	.80	.63	.69	.54
BUENOS AIRES Jan 66-Dec 75	1	1.14	1.46	--	.54	.54	
EDMONTON Jan 58-Dec 75	2	.96	.89	.88	.38	.48	.43
HUANCAYO Jan 65-Dec 75	1	2.05	1.66	1.73	.29	.42	.36
KODAIKANAL Jan 61-Apr 75	3	1.23	1.08	1.19	.56	.57	.48
MACQUARIE ISLES Jan 64-Dec 75	2	1.5	1.76	1.80	.58	.52	.54
MAUNA LOA Jan 64-Dec 75	4	.84	1.23	1.47	.54	.56	.50
TATENO Jan 58-Dec 75	2	.82	1.23	.88	.50	.56	.53
95% Significance Level						.36 ↑ .64	.38 ↑ .62
PRER., 60		1.70	1.57	1.52			
PRER., 120		1.60	1.47	1.42			

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values. The series is also long enough for statistically sig-
nificant data modeling and parameter estimation.

Analyzing the data consists of dividing each time series into
two parts, the earlier part to fit the model and the later part to
generate predictors which can be used to judge the difference between
the later observations and the earlier. Because of
the short length of the ozone series available, Pagano considered
three cases of dividing each ozone series into two parts:
(i) data through 1973 for modeling, 1974-75 data for predicting;
(ii) data through 1971 for modeling, 1972-75 data for predicting;
(iii) data through 1969 for modeling, 1970-75 data for predicting.
These three cases are referred to as data sets 2, 4, and 6,
respectively. Data set 2 yields the longest record for fitting
the model, and data set 6 yields the longest record for judging
the predictors.

The following is taken directly from Pagano's paper , as sub-
mitted to the proceedings, with the exception of italicized comments.

Tests for detecting changes in probability distribution and downward trends in time series

When the state of a system is describable by a time series $Y(t)$
of measurements over time, a natural question that arises is to test
a hypothesis H_0 that there have been no changes in the probability
distribution of the state of that system starting at a specified
time t_0. One approach to testing H_0, whose rationale has been dis-
cussed by Box and Tiao (1976) is as follows: (1) form a data base
of values $Y(t)$ at times denoted $t = 1, ..., T$; (2) fit a statistical
model to the time series $Y(\cdot)$, using its values only up to time t_0
where $t_0 < T$; (3) at each $t = 1, 2, ..., T$, form the one-step ahead
forecasts $Y(t)$ of the value $Y(t)$ at time based on the values
$Y(t-1)$, $Y(t-2)$,... at immediately preceding times; (4) comparison
of forecasts $Y^\mu(t)$ with actuality $Y(t)$ for $t > t_0$ can be used to
determine (qualitatively and quantitatively) whether the model for
the time series $Y(\cdot)$ fitted to the values before time t_0 describes
the probability distribution of the values $Y(t)$ at times after t_0.

One important diagnostic tool is the prediction error ratio,
abbreviated PRER. The mean square prediction errors before and
after t_0 are denoted

$$\text{PREDERRBEF } (t_0) = \frac{1}{t_0} \sum_{t=1}^{t_0} (Y(t) - Y^\mu(t))^2$$

$$\text{PREDERRAFT } (t_0) = \frac{1}{T-t_0} \sum_{t=t_0+1}^{T} (Y(t) - Y^\mu(t))^2$$

in terms of which we define

$$PRER\ (t_0) = \frac{PREDERRAFT\ (t_0)}{PREDERRBEF\ (t_0)}$$

Under the hypothesis that there has been no change in the model, the probability distribution of the statistic PRER (t_0) is <u>approximately</u> the F distribution with ($T-t_0$) and (t_0-p) degrees of freedom, where p is the number of parameters used in fitting the time series model.

The statistic PRER is a test statistic for the hypothesis of no model change at time t_0 which is an "omnibus" or "overall" criterion, in the sense that the test does not specify the nature of the change against which one is testing. One should also employ a "specific" test statistic which specifically tests for the kind of change one is concerned about detecting.

To test the hypothesis that there is a (downward) trend in the measurements, one would use the sign-test statistic

NEGER (t_0) = proportion of prediction errors

$$Y(t) - Y^\mu(t),\ t > t_0,$$

which are negative

If the process generating the data is stable, then the proportion of negative residuals (actual value Y(t) minus predicted value $Y^\mu(t)$) should be about 50%. *That is, Pagano commented, "We are just as likely to underpredict as to overpredict."* If the process measurements have a downward trend, then NEGER (the proportion of negative residuals) should be significantly greater than 50%. (If there is an upward trend, NEGER should be significantly less than 50%.) The expected variability of about 50% NEGER (t_0) when the hypothesis of no model change is true is described by the binomial distribution (with parameters t_0 and 0.5). Under the hypothesis of no model change, a 95% two-sided confidence region for NEGER (48) is 36% to 64%, and for NEGER (72) is 38% to 62% (see table 7).

Ninety-five percent significance levels for the value of PRER are approximately 1.70, 1.57, or 1.52, depending on whether the time span being predicted is the last two, four, or six years, and assuming that the degrees of freedom used in estimating the mean square prediction error over the fitted period is 60. For 120 degrees of freedom these thresholds are approximately 1.6, 1.47 and 1.42.

A technical note: inadvertently, instead of PREDERRBEF (t_0) we computed

$$\text{PREDERRTOT}(t_0) = \frac{1}{T}\sum_{t=1}^{T}\{Y(t) - Y^\mu(t)\}^2$$

using the model fitted to the data up to time t_0. One then computes PRER (t_0) using the relation

$$1 - \{\text{PRER}(t_0)\}^{-1} = \frac{T}{t_0}\left(1 - \left\{\frac{\text{PREDERRTOT}(t_0)}{\text{PREDERRAFT}(t_0)}\right\}\right)$$

Methods of time series model fitting

The first step in modeling a time series $Y(t)$ is to consider its level, or means. Since each station clearly exhibits a seasonal pattern (a 12-month periodicity), the monthly means (means of January, February, ..., December, respectively) are first calculated (Fig. 40, Fig. 41). A test is then performed to see if the monthly means can be represented as the sum of a small number of fundamental harmonics; this would achieve a reduction in the number of parameters required to model the mean. Usually the first two harmonics of the period 12 (frequency $2\pi/12$) suffice to model the monthly means by values called the fitted monthly means. The time series is then demeaned by subtracting from each monthly value the fitted mean for that month; the demeaned series is denoted $Z(t)$.
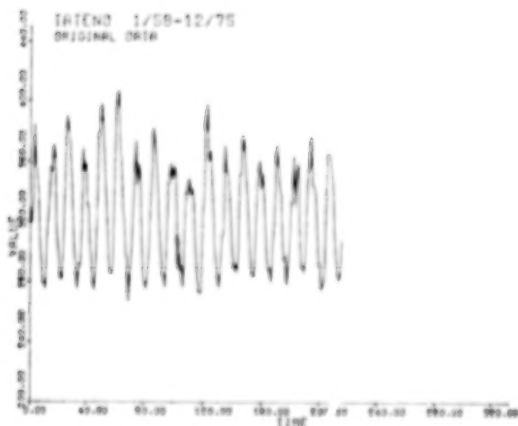
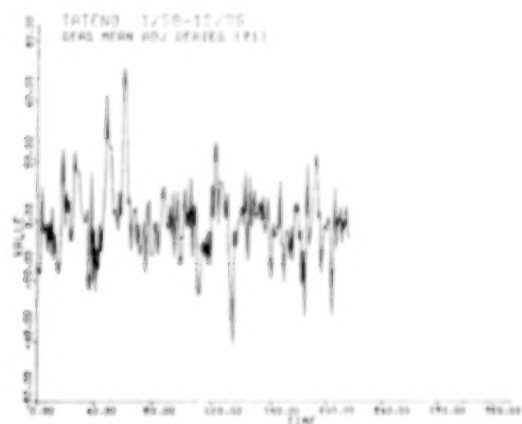Figure 40. Monthly Means, Original Data

Figure 41. Monthly Means, Seasonal Means Adjusted Series

The first step in modeling $Z(t)$, representing the fluctuations of a monthly time series $Y(t)$ about its fitted monthly means, is to examine the monthly variances; that is the variance of all January values about the fitted mean of January values, ..., the variance of all December values about the fitted mean of December values. Having calculated the monthly variances one would like to test the hypothesis that the variance is <u>constant</u> over the year. Tests of this hypothesis are available only under the simplifying assumption that time series is Gaussian white noise; it is felt that these tests can be used to provide a vague indication, on the basis of which most stations are regarded as having monthly variances which are not constant but vary. *"This correlation," Pagano added, "is exactly what we want--[we want to know] how dependent the future is on the past."* The only stations which we considered whose variances would be regarded as constant are Buenos Aires, Huancayo, and Kodaikanal.

When the monthly variances are regarded as constant we denote $Z(t)$ by $Z1(t)$. When the monthly variances are regarded as varying, we form a de-varianced time series $Z2(t)$ whose value for a given time t is $Z(t)$ divided by the monthly standard deviation for the month corresponding to time t.

For each series $Z1(\cdot)$ and $Z2(\cdot)$, we have two cases: the series is either stationary or periodic-stationary. To intuitively define these concepts, denote the series for expository purposes as $Z(t)$; we will model it as an autoregressive scheme (stochastic difference equation whose right-hand side $\epsilon(t)$ is white noise or independent random variables):

$$Z(t) + a_t(1)\, Z(t-1) + .. + a_t(m)\, Z(t-m) = \epsilon(t) \ .$$

Using a periodically varying filter rather than a static one, it is necessary to determine the filter length. Pagano pointed out that "statistical theory argues for a shorter filter to have fewer parameters, while reality argues for a long filter length."

$Z(\cdot)$ is stationary is equivalent to: the autoregressive co-efficients $a_t(j)$ do not depend on t and the variance of $\epsilon(t)$ is constant in t. How many autoregressive coefficients to use is determined by a statistical testing criterion; we consider two criteria which we call CAT and SELECT. $Z(t)$ is periodic-stationary is equivalent to: the coefficients $a_t(j)$ depend only on the month of t, and the variance of $\epsilon(t)$ also depends only on the month of t. In modeling period-stationary time series we consider three criteria for determining how many coefficients to use for a given month (described in methods 6, 7, 8 below).

The foregoing considerations yield eight possible models for the fluctuations $Z(\cdot)$ of a time series $Y(\cdot)$ about its monthly means.

Method 1: Treat monthly variances as constant, model Z1 as stationary time series, fit autoregressive scheme by CAT.

Method 2: Treat monthly variances as varying, model Z2 as stationary time series, fit autoregressive scheme by CAT.

Method 3: Same as method 1, but fit autoregressive scheme by SELECT.

Method 4: Same as method 2, but fit autoregressive scheme by SELECT.

Method 5: Treat monthly variances as constant, model Z1 as periodic-stationary, fit autoregressive schemes using order determined in method 1.

Method 6: Treat monthly variances as varying, model Z2 as periodic-stationary, fit autoregressive schemes using order determined in method 2.

Method 7: Same as method 6, but fit autoregressive schemes by PCAT for each month.

Method 8: Same as method 6, but fit autoregressive schemes by SELECT for each month.

The length of ozone time series does not seem long enough to use the model of periodic-stationary time series (methods 5, 6, 7 and 8) because of the number of parameters that need to be estimated. In our detailed data summaries, we report the model fitting results using these methods, but we explicitly consider interpretable only the model fitting results using methods 1 through 4.

To choose the most representative model for an ozone time series, the choice will be made from either methods 1, 3 or from methods 2,4 depending on whether one accepts or rejects the hypothesis that monthly variances are constant.

If one would like to select one of the models fitted as being "best fitting," a principle for choosing a modeling method is the following: choose the method which yields smallest overall mean square prediction error using PREDERRTOT on data set 2, and smallest mean square prediction error over the data set not used to fit the model using PREDERRAFT on data set 6. We believe that the conclusions are essentially similar for all models fitted by methods 1-4, but it seems worthwhile to choose one method as being most representative. The test statistics for this method are reported in Table 7.

Table 8. Autoregressive filter of model fitted to fluctuations $Z(t)$

$$Z(t) + \alpha_1 Z(t-1) + \ldots + \alpha_m Z(t-m) = \varepsilon(t)$$

STATION	DATA SET	α_1	α_2	α_3	α_4	α_5	α_6	α_7
AROSA	2	-.061	-.130	-.048	-.102	-.048	-.153	
	4	-.126	-.135	-.041	-.135	-.057	-.158	.112
	6	-.190	-.141					
ASPENDALE	2	-.283	-.163	-.193				
	4	-.189	-.097	-.214	-.050	-.178	.035	-.025
		-.001	.090	.209	(coefficients α_8, α_9, α_{10})			
	6	-.203	-.165	-.229				
BUENOS AIRES	2	-.257						
	4	-.371						
EDMONTON	2	-.097	-.118	-.028	-.067	-.146		
	4	-.148	-.048	-.073	-.073	-.159		
	6	-.140	-.059	-.070	-.085	-.202		
HUANCAYO	2	-.476	-.195					
	4	-.652						
	6	-.637						
KODAIKANAL	2	-.713	0	0	-.222			
	4	-.730	0	0	-.200			
	6	-.875						
MACQUARIE ISLES	2	-.323	-.068	-.091	.217			
	4	-.382						
	6	-.434	.174					
MAUNA LOA	2	-.576						
	4	-.470						
	6	-.457						
TATENO	2	-.247	-.285					
	4	-.312	-.253					
	6	-.384						

Table 8 summarizes the coefficients of the stationary auto-regressive models fitted to the fluctuation series $Z(t)$ at each station.

Since this methodology should work with any parameter that
varies seasonally, London proposed applying the same technique
to temperature data to see if the methodology successfully predicts
the world-wide cooling that has occurred since the 1940s. If the
technique does forecast the temperature change, it would clearly
strengthen the methodology and lend greater evidence to the con-
clusions about other seasonal variations such as ozone.

Conclusions

The values of the test statistics summarized in Table 7 do not
reject the hypothesis that there has been no downward trend in the
measurements of ozone levels in the period through 1975.

By the test statistic NEGER (proportion of negative forecast
errors) Arosa and Aspendale could be considered to have a sig-
nificantly high proportion in their forecasts over 1971-75, but
not over 1969-75. Their values of the test statistic PRER is not
significantly high.

The values of PRER for Huancayo are significantly high which
indicates a change in the probability distributions of ozone levels;
to interpret this one uses the values of NEGER which are just barely
significantly low for Huancayo. Therefore, if there is any statis-
tical evidence of trend in ozone measurements at Huancayo, it is an
upward trend.

On the other hand, the values of PRER for Macquarie Islands
are significantly high, but NEGER is non-significant. Therefore,
the ozone measurements at Macquarie Isles might provide statistical
evidence of a downward trend. It is the only station with this
property. It is also the station for which our time series model
fits the worst when one compares the mean square forecast error with
the overall variance of the time series (summarized in Table 9).

Table 9. Comparison of mean square forecast errors with overall variance of time series

STATION	MEAN	VARIANCE	MEAN SQUARED FORECAST ERROR PREDERRAFT	
			Last 4 Years	Last 6 Years
AROSA	334.3	245.5	283.1	276.1
ASPENDALE	320.2	138.2	94.7	79.4
BUENOS AIRES	287.9	152.9	168.6	
EDMONTON	358.0	324.0	250.1	252.8
HUANCAYO	263.5	22.8	21.4	22.0
KODAIKANAL	261.2	103.6	19.1	20.0
MACQUARIE ISLES	340.5	374.3	462.1	455.1
MAUNA LOA	277.1	78.4	59.7	66.2
TATENO	324.6	179.4	123.9	113.3

Janet Campbell of NASA Langley reviewed the "imperfect data question." She defined the following terms:

$\hat{0}_3(t,x)$ = Dobson measurement

$0_3(t,x)$ = Actual total ozone

where both are associated with a time t and position x. The error associated with this measurement is:

$$\epsilon(t,x) = \hat{0}_3(t,x) - 0_3(t,x)$$

In order to determine data quality, one must know something about the properties of $\epsilon(t,x)$.

Campbell showed two data records which were made simultaneously by side-by-side Dobson instruments at Arosa, Switzerland. Since both instruments are attempting to measure the same $0_3(t,x)$, then differences in simultaneous measurements are, essentially, differences in errors. Thus, one can gain some insight into the magnitude of errors at this station by examining these differences.

Writing:

$$\text{known} \leftarrow \quad \text{unknown}$$
$$\hat{O}_3(t,x) \quad = \quad O_3(t,x) + \epsilon(t,x)$$

and noting that the left-hand side of the equation is the known (observable) information and the right-hand side represents an unknown partitioning, then the known average of a set of Dobson measurements is an estimate of the average true ozone plus the average error (bias). That is:

$$\text{known} \leftarrow \quad \text{unknown}$$
$$E(\hat{O}_3(t,x)) \quad = \quad E(O_3(t,x)) + E(\epsilon(t,x))$$

If $\epsilon(t,x)$ is unbiased, then $E(\epsilon(t,x))$ tends to zero for a "long enough" averaging period. The assumption of no bias may not be reasonable, however.

Trend estimates are limited by the variance of the data, that is, by:

$$\text{known} \leftarrow \quad \text{unknown}$$
$$Var(\hat{O}_3(t,x)) \quad = \quad Var(O_3(t,x)) + Var(\epsilon(t,x)) + 2\, Cov(O_3,\epsilon)$$

It is desirable for the errors to be independent of the actual total ozone (i.e., $Cov(O_3,\epsilon) = 0$). If this is the case, then

$$Var(\hat{O}_3(t,x)) \geq Var(O_3(t,x))$$

and

$$Var(\hat{O}_3(t,x)) \geq Var(\epsilon(t,x))$$

so that the known data variance provides an upper bound on the variances of O_3 and ϵ.

To decide about the existence of a bias or whether or not errors are correlated to O_3, one should "pull the errors apart" and look at potential error sources. Three major causes of error are:

1. incorrect instrument calibration, poor maintenance, etc.

2. algorithms used to convert measured radiances to total ozone estimates

3. meteorological/geophysical variables.

A calibration error, for example, could produce either a constant bias or a time-varying bias (drift) in the data. Correlations between ϵ and O_3 can result from the correlation of both with a third variable such as another atmospheric constituent.

There are some types of errors which can seriously affect trend estimation techniques whereas others are not so serious. An unknown but constant bias will not affect trend estimates, whereas a bias which changes over time can either be mistaken for an ozone trend or cancel a real ozone trend of opposite sign. The actual magnitude of errors is not necessarily a problem because this is accounted for in the trend estimation techniques, provided that the data variance properly reflects these magnitudes. This condition will be met, as discussed earlier, if $Cov(O_3,\epsilon) = 0$. It is important to examine error sources and attempt to identify or remove the serious errors.

There are two possible mistakes which can be made in our conclusions. The "Type I" mistake would occur if we were to detect a trend which doesn't exist, and the "Type II" mistake would result if we were to fail to detect a trend which does exist. As previously mentioned, errors which contain a trend in themselves could result in either of these mistakes. A Type I error could also result from too short a data record when a natural low frequency oscillation is mistaken for a monotonic trend. A Type II error can result from an inadequate model in which residual variances are too high. The models of Hill, Sheldon and Tiede, with their low trend detectability thresholds, do not suffer from this problem. The major type of data inadequacy which can invalidate their results would be trending errors.

(Campbell noted: "This discussion of errors applies only to situations where one is analyzing time series at one or more stations and making inferences about those stations. Where inferences are 'extrapolated' beyond the stations for which data are available, as for example, a global mean estimated using data from 9 stations, other errors can occur and these are not addressed here.")

Komhyr emphasized the importance of Type I errors where the "net effect could be no trend" and suggested that it might be useful to look at variations in different levels of the atmosphere. He added, "Statistical analysis can tell you if a trend is going on or not, but physical and chemical analysis must explain the data."

Gille observed that the ozone concentration in the 40-km region reflects the first effects of photochemistry. Since the natural variance of ozone concentration is thought to be low at this altitude, it is a good place to look for the first evidence of changes in ozone photochemistry. In addition, the variance in limb scanning data is low at this altitude, giving two reasons for an improved signal-to-noise ratio.

The second day was opened by A. Barrie Pittock who made a plea
for including physical understanding of sources of variances and
the physical processes in the atmosphere. Statistical models
looking at the data set without knowing what is going on are likely
to be misleading. He cited the classic example of water levels in
Lake Victoria which showed two nice 11-year cycles prior to the
early 1920s that correlated with sunspots, but then showed much
shorter, small amplitude cycles until the early 1960s. A massive
rise of more than a meter then took place and levels have dropped
only slowly since then.

To illustrate his point that physical insights can make sense
of climatic series and provide evidence of causal relationships,
Pittock showed a time series of precipitation in Seattle with an
apparent anomalous increase in rainfall in the Puget Sound area
since 1940. He then showed how this apparent anomaly can be
accounted for meteorologically with the location of high pressure.
"Thus," Pittock concluded, "we can use one physical time series
to account for another."

Pittock pointed out the high variability of atmospheric ozone
content, the variance of which changes markedly with altitude
(Fig. 42), and showed the results of a recent analysis which broke
the total variance in ozone over Aspendale (38S) down into components
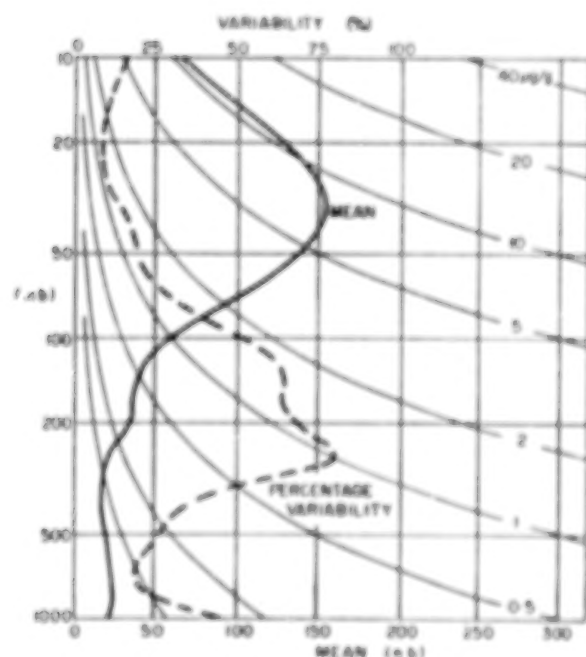having different time scales and possible causes (Fig. 43).
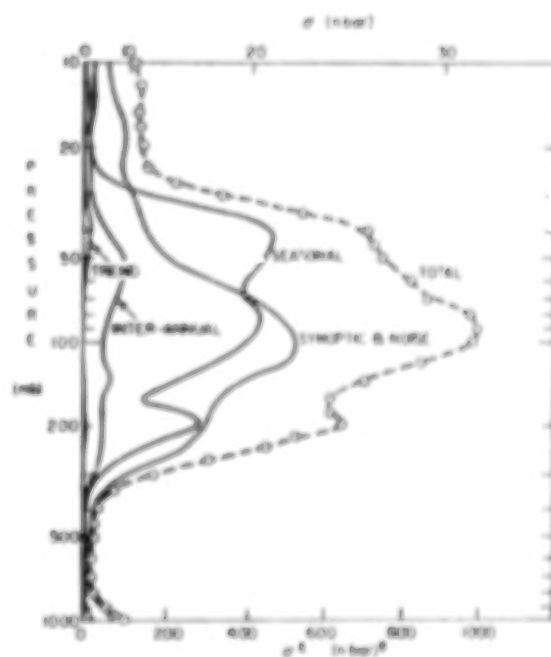

Figure 42.   Variability of Atmospheric   Figure 43.   Components of Variance
             Ozone Content   in Ozone over Aspendale

Noting that spatial patterns of variation give clues to the physics behind them, Pittock stressed the need to identify regions/stations which should be monitored to understand apparent trends.

In specific reference to Hill's methodology, Pittock said, "It is not just a matter of selecting equal area boxes but worrying about where the boxes are."

Spatial patterns of mean distributions or patterns of change, or eigenvector characteristic patterns, or patterns of correlations between stations or with circulation parameters can be used.

In eigenvector analysis, usually 80% to 90% of the total variance can be accounted for by the first eight or so patterns. So, Pittock suggested identifying patterns which account for the variances, then looking for what might cause them.

Pittock continued, "A few such patterns usually account for most of the variance, leading to physical hypotheses concerning causal relationships which can be tested." The dominant patterns in many climatic variations are standing waves, due to orographic effects and land-sea distribution, and patterns related to the strength of the Hadley circulation. These mechanisms, which operate on ozone, largely account for correlations between stations (Fig. 44) and suggest where monitoring stations should be located. Ozone in the southern hemisphere is highly correlated with the latitude of the high pressure belt (Fig. 45).

Correlations R, between Spring (ASO) mean total ozone amounts between various pairs of Southern Hemisphere stations. N is the number of data pairs, R^2 is the percentage of the variance accounted for by the correlation, and P is the percentage probability that the correlation has occurred by chance.

STATIONS	N	R	R^2	P
Hobart & Wellington v Aspendale	9	0.85	72	< 1
Macquarie Isle v Aspendale	10	0.81	66	< 1
Amundsen-Scott & Byrd v Aspendale	11	0.77	59	< 1
Brisbane v Aspendale	14	0.73	54	< 1
Darwin v Aspendale	5	0.20	4	large
Argentine Island v Aspendale	8	-0.33	11	large
Darwin v Brisbane	5	0.44	20	large

Figure 44. Correlations Between Stations

Time series of amplitudes of
characteristic patterns should be
monitored and compared with
correlated circulation indices.
A breakdown in well-established
correlations between ozone varia-
tions and variations in other
atmospheric parameters or indices
would suggest the need to inves-
tigate anthropogenic causes.

Hypotheses as to anthropo-
genic causes should be tested by
correlating indices of hypothesized
causes, intermediate effects and
corollaries, as well as effects on
ozone. Pittock concluded, "If there
is a change occurring and there is
not a change occurring in the
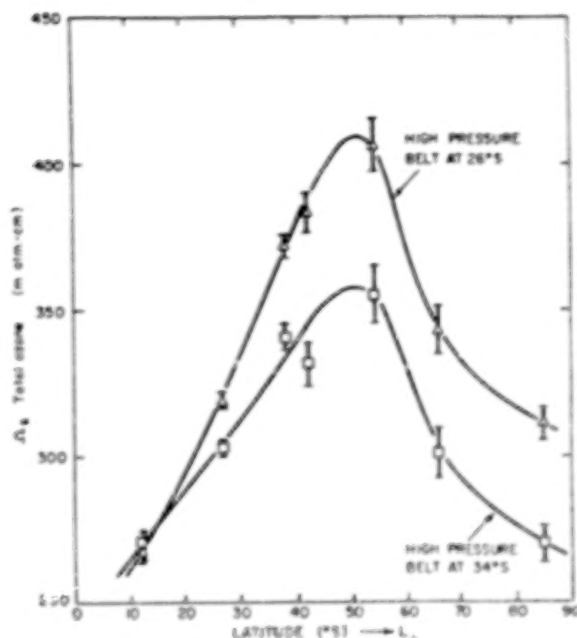general circulation, then we'd
get very suspicious."

Figure 45. Total Ozone Versus
Latitude

London presented information that the largest variance occurs
with the largest ozone buildup (in winter), not at the largest total
amount of ozone, to which Tukey added that "in a system with feed-
back, arguing with lags is hanging over an abyss because to say it
occurs is also to say the reverse is true."

Lovill next discussed a paper, Temporal Variability of Total
Ozone During 1957-75, written with his Lawrence Livermore
Laboratory colleagues Thomas J. Sullivan and John A. Korver.
The paper, as submitted to the proceedings,follows.

There are 152 stations that have taken total ozone observations.
The length of record varies from 6,618 days (July 1957-December
1975) with observations taken at Aspendale, Australia to as few as
six days at Woomera, Australia. This paper will use only the data
from 15 of these 152 stations. The stations were selected on the
basis of longevity of record and their individual standard
deviation (σ). Each of these 15 stations has a minimum record
data length of 18 years. The standard deviation of ozone values at
a station is primarily a function of the instrument calibration and
daily meteorological variability.

We have calculated the standard deviation of total ozone variations at a subset of 99 stations. These stations are located as shown in Figure 46 (a,b) and their σ's are indicated in Figure 47 (a,b) and Table 10. It is readily obvious that the σ's increase in value from lower to higher latitudes. The standard deviations range from as low as 9 m atm-cm at Huancayo, Peru to as high as 108 m atm-cm at Yakutsk, U.S.S.R.

It is worthwhile to compare the σ's at stations in similar latitude bands in order to obtain an estimation of individual station meteorological variability and instrumental accuracy. The σ's at stations in North America compare well with those in Western Europe at selected latitude bands. A comparison of the Western European and North American data with those of the Japanese stations also indicates similar values as a function of latitude. However σ's at many stations in the Soviet Union do not compare well with the data from North America, Japan, and Western Europe. In the southern hemisphere there are considerably fewer stations and the σ variability is large. Two stations do appear to deviate significantly from the average for their latitude band: these are Port aux Francais (σ = 83 m atm-cm) and Dumont d'Urville (σ = 85 m atm-cm).

Next we looked at regional total ozone variations during the 18-year period by combining the individual station records for selected regions (Figs. 48-51).

When this is done for the two Canadian stations ozone is observed to increase irregularly until 1966; thereafter it irregularly de-creases. The combined record of the three Japanese stations indi-cates an irregular, slow increase of ozone that is continuing until the present. The two Australian stations indicate an irregular decrease of ozone continuing until the present. The Indian stations show a strong increase of ozone until 1964 and thereafter a slower increase and since ∿ 1970 a steady amount.

Next we have expanded our coverage using these 15 stations until it is global in extent. We will look at two different techniques for analyzing these 15 stations, which we think represent the best long-term data record available. In Figure 52 we have plotted the 18 years of data from the 15 stations such that each station contributes equally. These data in Figure 52, which are strongly biased toward the Northern Hemisphere (especially Europe) indicate an increase of total ozone until ∿ 1970 and thereafter a decrease. Figure 53 weights the station data in the Northern Hemisphere equally with those from the Southern Hemisphere. In this figure it is very difficult to determine a trend of any significance.
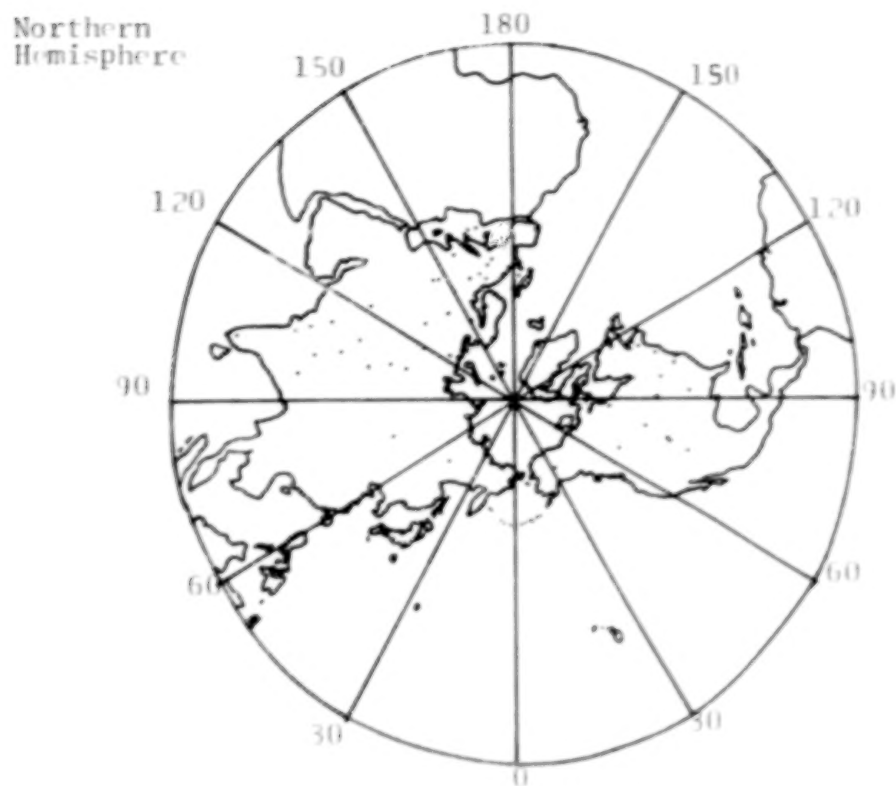
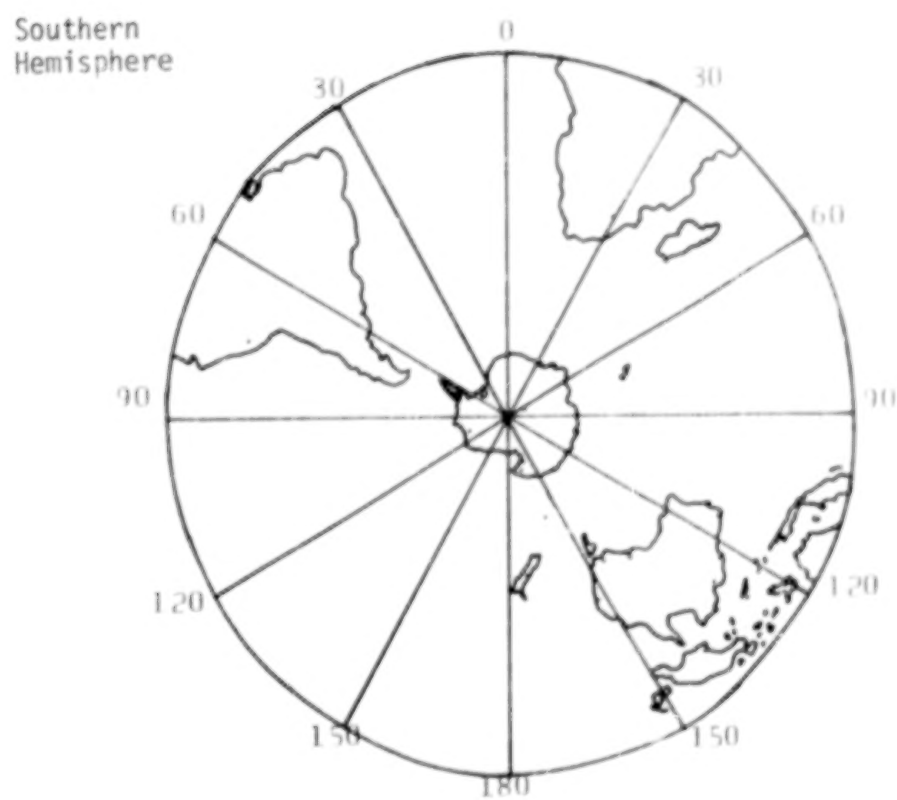Figure 46a. Northern Hemisphere Station Locations

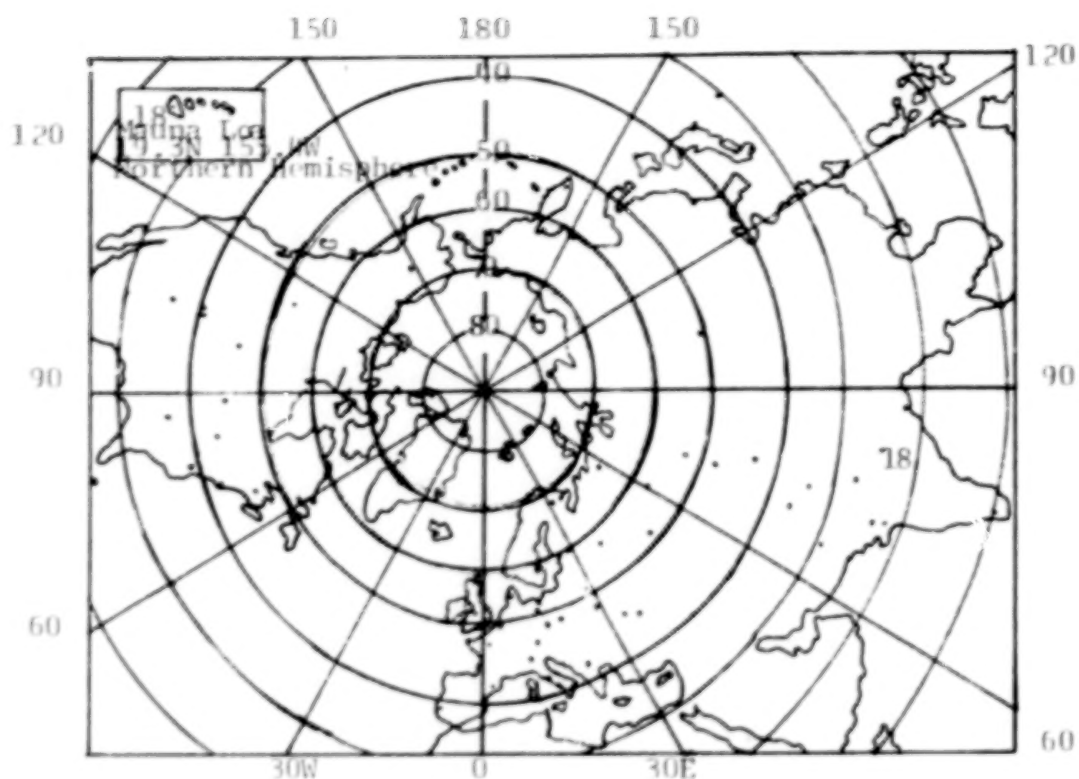Figure 46b. Southern Hemisphere Station Locations

Figure 47a. Northern Hemisphere Total Ozone Observatory Stations
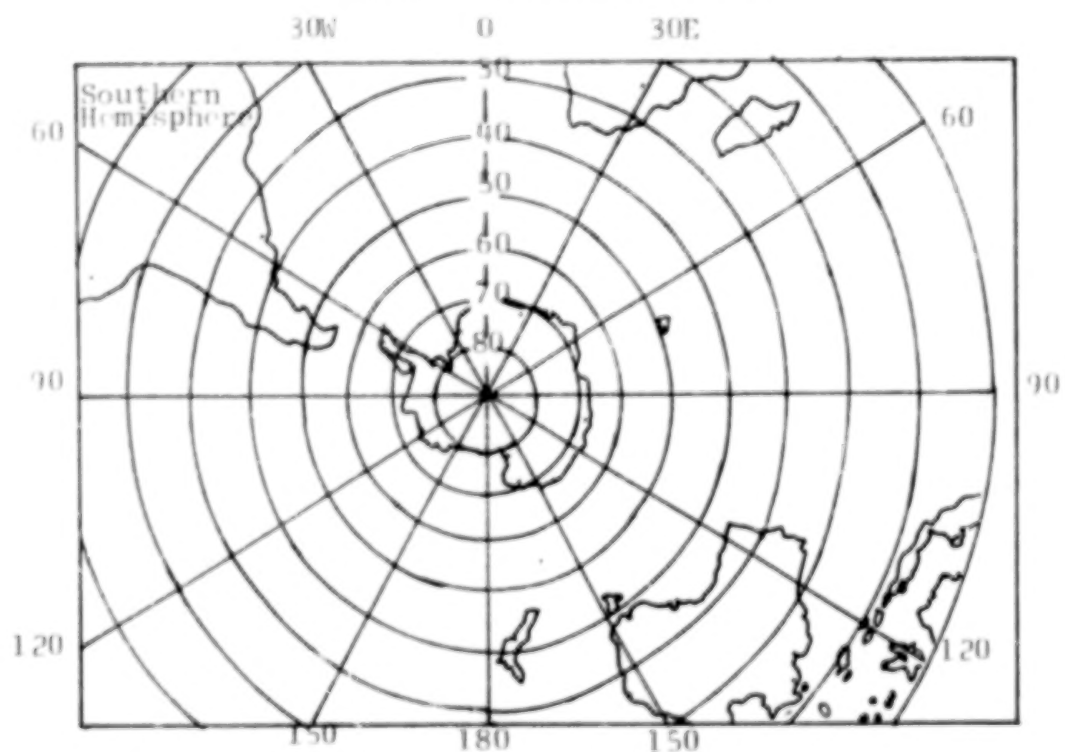Used to Calculate Standard Deviations

Figure 47b. Southern Hemisphere Total Ozone Observatory Stations
Used to Calculate Standard Deviations

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Table 10. Ninety-nine stations and their standard deviations

Station Number	Station Name	σ	Ō₃	No. of Observations	Latitude	Longitude	Station Number	Station Name	σ	Ō₃	No. of Observations	Latitude	Longitude
3	Alma Alta	67	321	4521	43.1N	76.5E	42	Leningrad	65	350	3997	59.5N	30.2E
5	Dikson Island	103	364	1502	73.3N	80.1E	43	Lerwick	60	354	4513	60.1N	1.1E
7	Kagoshima	30	289	5804	31.4N	130.3E	44	Spitzbergen	67	353	987	78.1N	15.4E
8	Kodaikanal	18	257	4457	10.1N	77.3E	45	Messina	40	343	6342	38.1N	15.3E
9	Mount Abu	17	255	2678	24.4N	72.4E	47	Naples	40	299	3139	40.5N	14.2E
10	New Delhi	21	272	5974	28.4N	77.1E	48	Oxford	53	356	5328	51.5N	1.1W
11	Quetta	30	277	3325	30.1N	66.5E	50	Potsdam	50	347	3024	52.'N	13.0E
12	Sapporo	61	368	5918	43.0N	141.2E	51	Reykjavik	61	339	3179	64.3N	21.5W
13	Spinagar	26	292	4408	34.0N	74.5E	52	Tromso	75	337	2474	69.4N	18.5E
14	Tateno	42	323	6515	36.0N	140.0E	53	Uccle	51	351	1411	50.5N	4.2E
15	Torishima	31	287	1404	30.3N	140.2E	54	Uppsala	64	329	439	59.5N	17.4E
16	Vladivostok	82	358	4577	43.1N	131.5E	55	Vigna Di Valle	44	341	6458	42.1N	12.1E
17	Argentine Island	45	319	2310	65.2S	64.2W	57	Halley Bay	40	315	1999	75.3S	26.4W
19	Bismark	50	349	4946	46.5N	100.5W	58	Little America	83	318	152	78.0S	162.0W
20	Caribou	54	370	4098	46.5N	68.0W	62	Port Aux Francais	83	375	973	49.2S	70.2E
21	Edmonton	55	356	6278	53.3N	114.0W	64	Sterling	42	340	1689	38.5N	77.3W
22	Green Bay	49	358	4513	44.3N	88.1W	65	Toronto	52	362	4298	43.4N	79.1W
23	Moosonee	57	378	1356	51.2N	80.4W	66	Ft. Collins	39	310	1418	40.3N	105.0W
24	Resolute	78	390	3878	74.4N	94.5W	67	Boulder	40	332	2577	40.0N	105.2W
26	Aspendale	36	320	6618	38.0S	145.0E	68	Belsk	50	341	3971	50.5N	20.5E
27	Brisbane	24	291	5280	27.3S	153.0E	69	Hallett	41	339	400	72.2S	170.1E
28	Dumont d'Urville	85	317	333	66.4S	140.0E	70	Mont Louis	42	336	4450	42.3N	2.1E
29	Macquarie Isl.	50	342	4216	54.3S	158.5E	71	Pretoria	15	260	1799	25.5S	28.1E
30	Marcus Island	28	270	1970	24.2N	153.5E	72	Byrd	45	318	947	80.0S	119.3W
31	Mauna Loa	18	276	3372	19.3N	155.4W	73	Ahmedabad	16	253	3309	23.0N	72.4E
32	Wellington	43	316	1622	41.2S	174.5E	74	Varanasi	18	280	4071	25.3N	82.5E
34	Arhus	63	351	5864	56.1N	10.1E	75	Dumdum	17	268	2580	22.4N	88.3E
35	Arosa	45	331	4879	46.5N	9.4E	76	Goose	59	380	4752	53.2N	60.2W
36	Camborne	49	335	2577	50.1N	5.2W	77	Churchill	62	387	3572	58.5N	94.0W
38	Elmas/Cagliari	40	331	6011	39.2N	9.0E	79	Tallahassee	26	306	2432	30.3N	84.2W

Table 10 continued.

Station Number	Station Name	σ	$\bar{O}_3$	No. of Observations	Latitude	Longitude
80	Gan	15	264	2215	0.4S	73.1E
81	King Bedouin	30	330	460	70.3S	24.2E
82	Lisbon	40	301	2235	38.5W	9.1W
84	Darwin	12	264	2706	12.3S	130.5E
85	Irkutsk	93	382	3003	52.2N	104.2E
86	Karadag	69	302	1927	45.0N	35.2E
87	Kiev	66	338	3880	50.2N	30.3E
88	Mirny	58	315	460	66.3S	93.0E
90	Ashkahabad	58	277	4188	37.5N	58.2E
91	Buenos Aires	28	287	1472	34.4S	58.3W
92	Hobart	40	327	2241	42.5S	147.2E
96	Hradec Kralove	51	335	3103	50.1N	15.5E
98	Val Joyeux	62	304	1801	48.5N	2.0E
99	Hohenpeissenberg	46	338	1770	47.5N	11.0E
101	Syowa	47	342	892	69.0S	39.4E
102	Bracknell	49	352	1512	51.3N	0.5W
103	Albuquerque	32	297	1493	35.1N	106.4W
104	Bedford	49	357	1569	42.3N	71.2W
105	Fairbanks	59	383	1288	64.5N	147.5W
106	Nashville	36	334	3836	36.2N	86.3W
107	Wallops Island	38	327	1779	37.5N	75.3W
110	Huancayo	9	263	3797	12.0S	75.2W
111	Amundsen-Scott	41	325	1377	90.0S	0.0W
112	Bolshaya Elan	89	364	3118	46.5N	142.4E
113	Dushanbe	64	278	3454	38.4N	68.5E
115	Kuibyshev	75	330	3328	53.2N	50.3E
116	Moscow	79	327	2874	55.5N	37.4E
117	Murmansk	87	354	2803	68.5N	33.0E
118	Nagaevo	102	386	2576	59.4N	150.5E
119	Odessa	71	329	3430	46.3N	30.4E

Station Number	Station Name	σ	$\bar{O}_3$	No. of Observations	Latitude	Longitude
120	Omsk	77	369	3494	54.5N	73.2E
121	Riga	74	348	3411 [1]	56.5N	24.0E
122	Sverdlovsk	69	354	4103	56.5N	60.4E
123	Yakutsk	108	366	2668	62.1N	129.5E
128	Karaganda	62	269	1019	49.5N	73.1E
129	Pechora	85	303	955	65.1N	57.1E
130	Petropavlovsk	87	357	1277	52.5N	158.5E
132	Sofia	41	314	921	42.5N	23.2
159	Perth	79	295	2314	31.5S	115.1E

[1] Key Stations
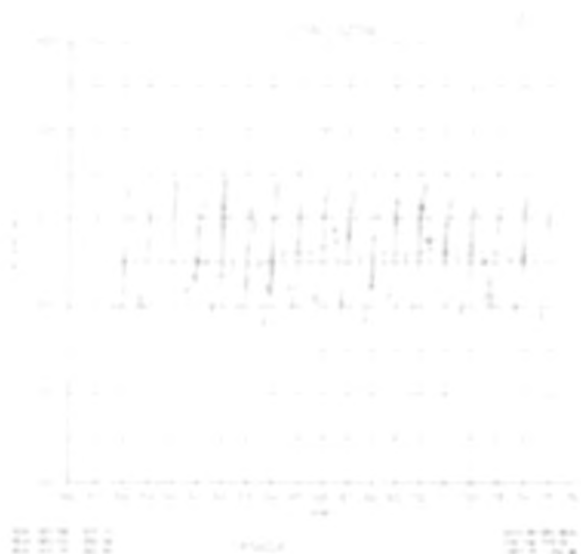
Figure 48. Ozone Variations at
            Canada

Figure 49. Ozone Variations at
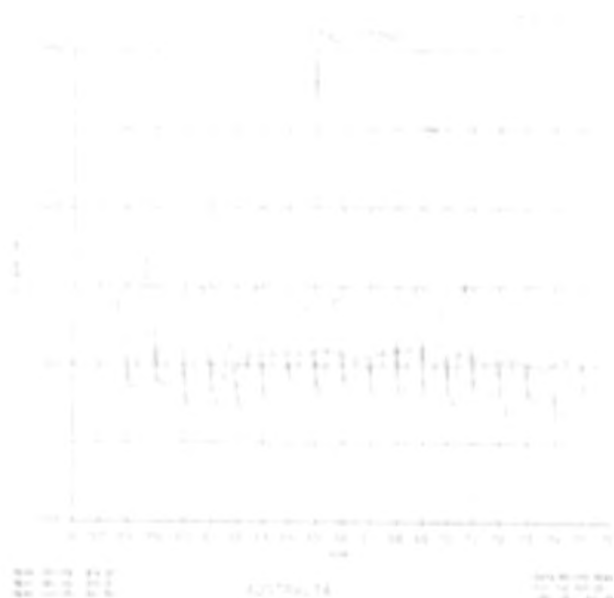   Japan

Figure 50. Ozone Variations at
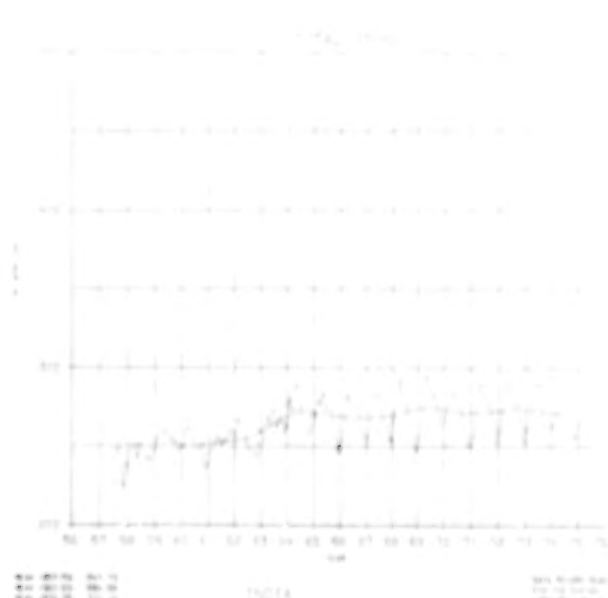   Australia

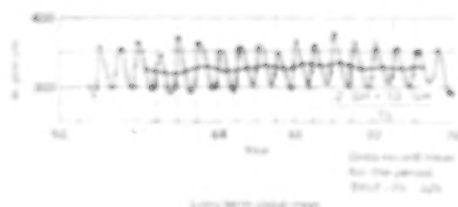Figure 51. Ozone Variations at
            India

75

Figure 52. Ozone Content, Each
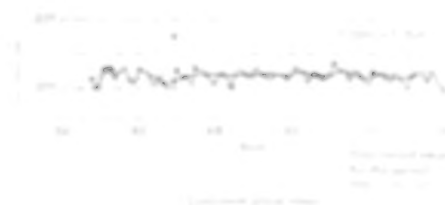Station Weighted Equally

Figure 53. Ozone Content, Each
Hemisphere Weighted Equally

Both data sets do show a decrease of ozone after ∿ 1970 and a distinct minimum in 1961.

It is our conclusion that a carefully selected data set of 15 stations indicates no obvious long-term trends in global total ozone. Because of the data sparsity over the oceanic regions and the strong bias toward the Northern Hemisphere (and especially Europe), we feel that analysts should utilize the total ozone data available with caution and careful inspection of parameters, such as the station o's.

SATELLITE ANALYSIS

Figure 54 indicates ɔ days of total ozone data as measured by the Nimbus 3 IRIS se: These data have been latitudinally weighted to remove areal bias. The data extend through a period starting with the Northern Hemisphere spring (Southern Hemisphere fall) and ending with the Northern Hemisphere summer (Southern Hemisphere winter). The standard deviation for the data set is 2.6 m atm-cm.

During this period there was approximately 5% more total ozone observed by satellite in the Northern Hemisphere (318 m atm-cm) than in the Southern Hemisphere (303 m atm-cm) (Table 11).
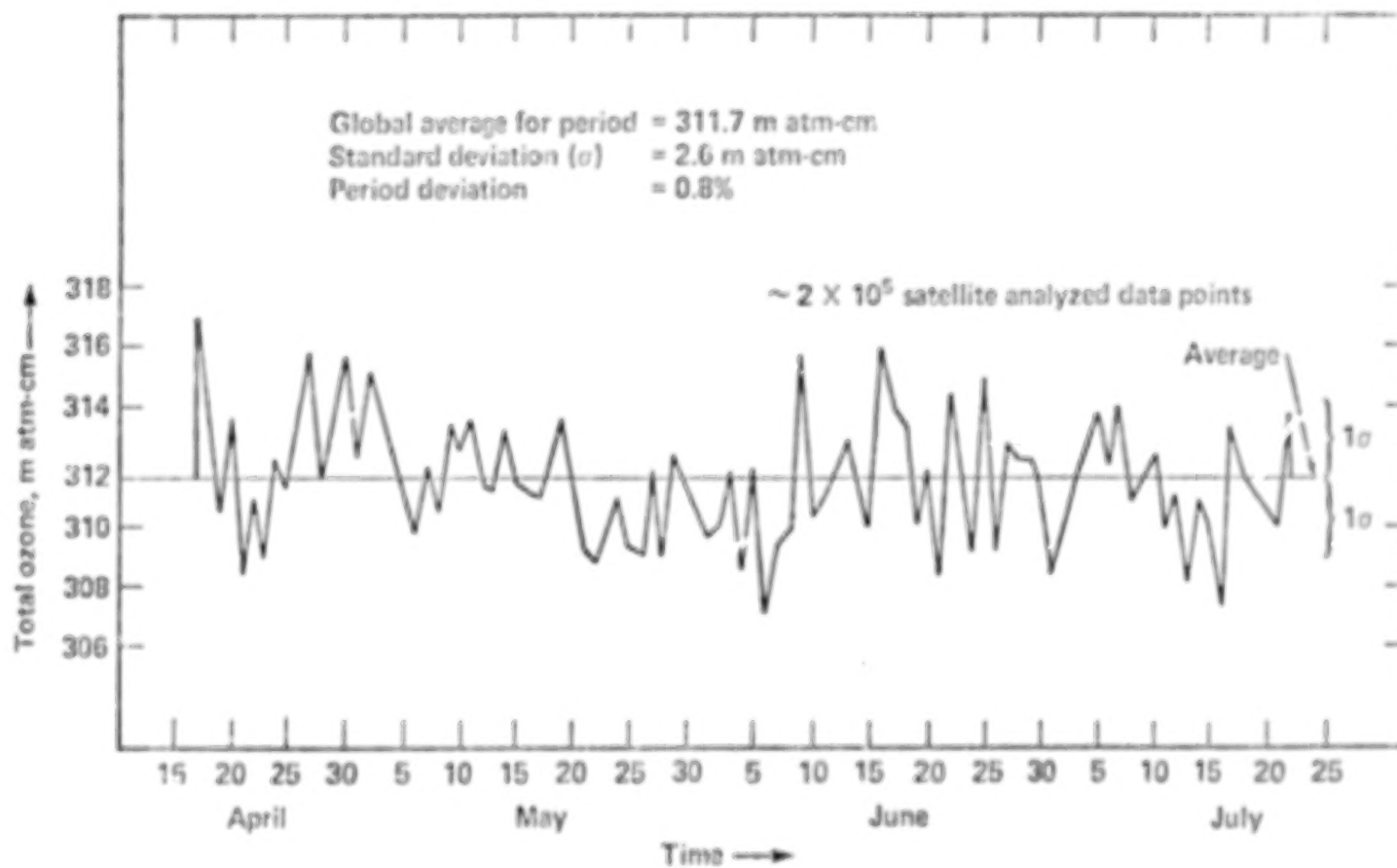
Figure 54. Total Ozone Data Measured by
Nimbus 3 IRIS Sensor

CONTENTS

Table 11. Land and Sea Distribution of Total Ozone
          (April 16-July 22, 1969; Nimbus 3; 1.85 × 10
          data points; values in m atm-cm).

	Land	Sea	Total	Standard Deviation	Sea-Land (m atm-cm)	Sea-Land %
Global	310.3	312.1	311.7	2.6	1.8	0.58%
No. Hemis.	315.8	319.1	318.1	7.8	3.5	1.04%
So. Hemis.	302.9	303.1	303.1	8.9	0.2	0.07%
$30°N-60°N$	337.5	344.1	341.6	14 3	6.6	1.96%

Perry Gluckmar presented his time series analysis which was done in the frequency domain rather than the time domain. His analysis tended to corroborate what other speakers had presented. Details of his presentation are not available for the proceedings.

John Tukey of Princeton University discussed the use of exogenous variables. "While I do not for a moment undervalue physical insight or physical explanation, it is important to keep in mind that purely statistical considerations call for making adjustments of empirical size for any internally reliable exogenous variable that could possibly make sense.

"We ought to do more to find and use exogenous variables."
He concluded by suggesting some exogenous variables that might
help:

- Pittock's general circulation quantities

- Reiter's energy sloshing and vacillation

- Gluckman's intermonth adjustment to fixed dates

- Gluckman's sector crossings - field reversal

- ??? geomagnetic character figures

Others suggested by conferees included:

- local winds aloft

- local barometer

- local height of tropopause

Tukey said, "Suppose we do adjust for the local barometer, then
collect the global mean. Then we must think carefully about the
interpretation if the mean barometric pattern is changing." London
noted that this was already done, at least in part, in Pittock's
general circulation.

Tukey summarized his suggestion to "use the things we can
trust--such as local pressure--and see what happens when we use
them and then look for explanations." London responded that the
key problem is the use of extra information in terms of filtering.
"You are bringing up the key to the filtering problem in getting
the real information." Tukey agreed saying we should "use all
available principles of witchcraft and if some are roughly orthogonal
we should use both." He restated Hill's methodology as using
persistence and shocks to see what they tell us, then focusing the
analysis on the shocks. This methodology, Tukey said, "does get
you out of certain technical problems; it saves trouble with the
data Hill had. If we can provide better data, perhaps he can do
better." But Tukey concluded, "We cannot bypass Basher."

James K. Angell, of NOAA, compared ozone trends with
stratospheric water vapor, the temperature of the equatorial
tropopause, and the north temperate latitude temperature (Fig. 55)
to illustrate what he termed some "very interesting" results.
Although the water vapor data record is short, beginning in 1964,
and there are not many measurements (only one a month at the most),
the total ozone is very well correlated with water vapor and
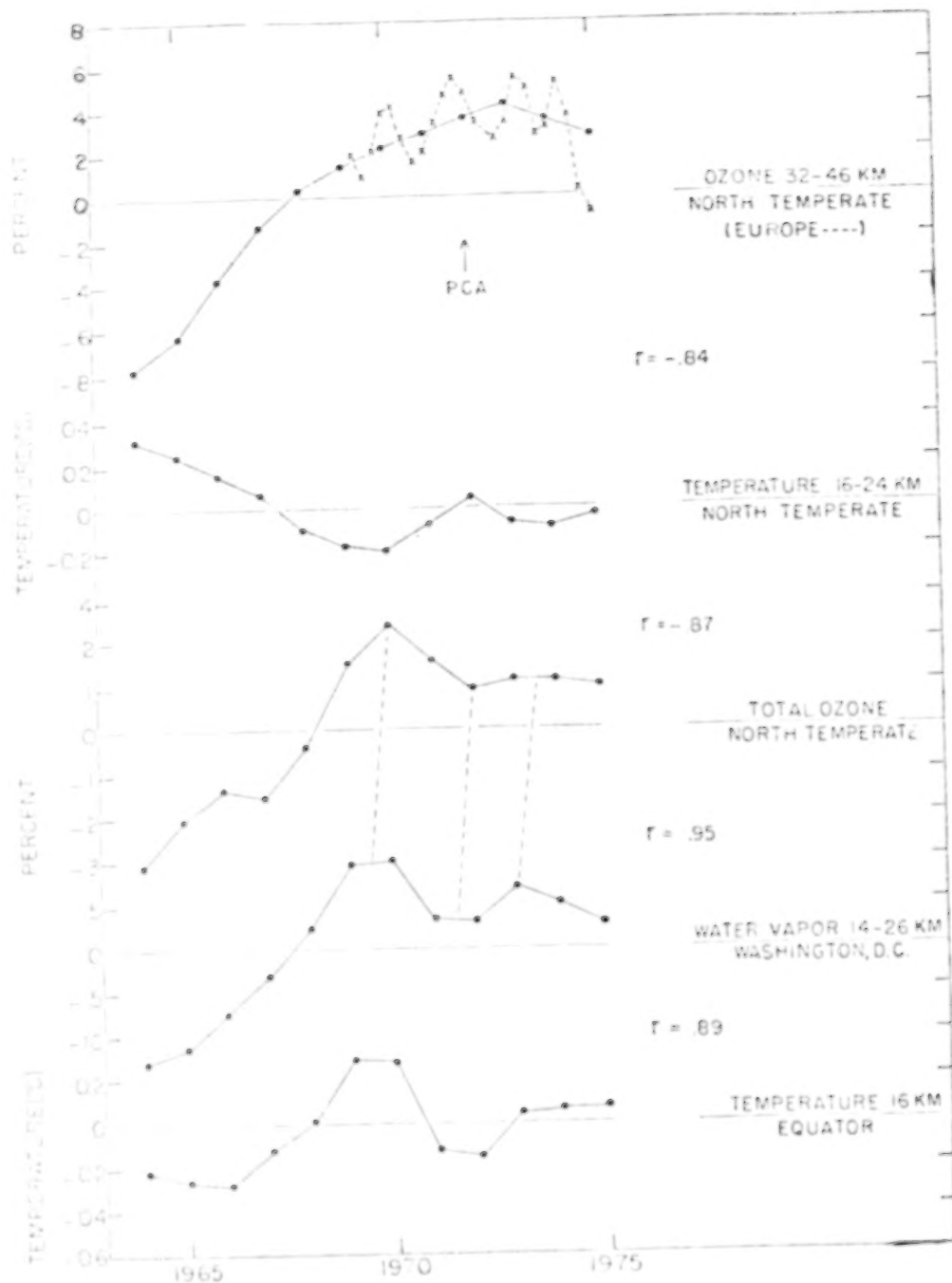distinctly out of phase with stratospheric temperatures. That

Figure 55. Comparison of Ozone Trends with Stratospheric Water Vapor, Temperature of Equatorial Tropopause, and North Temperate Latitude Temperature

is, the maximum ozone occurs when the
stratospheric temperature is the lowest,
an unexpected result for which Reiter
offered a meteorological explanation:
stratospheric water vapor comes mostly
from summer monsoons whereas ozone is
a winter characteristic. He further
suggested that the anticorrelation of
temperature may be due to pressure
distributions as suggested earlier by
Pittock.

Angell expanded the puzzle with
Umkehr data (Fig. 56) noting that,
"If you accept Umkehr data, we see an
increase instead of the expected de-
crease due to CFMs. This problem is
not really resolved but, where we
should see a 5% decrease and we see
instead 12% the other way, it makes
us wonder."

In subsequent discussion Angell
pointed out that an anomaly in the data
coincides with the eruption of Agung,   Figure 56. Umkehr Data
leading him to question how Hill's
analysis deals with such an anomaly.
Hill said that he had misunderstood
the previous question and that indeed
the volcanic effect was in his analysis and that his techniques
certainly try to quantify such interventions. Tukey elaborated
that Hill's pre-whitening filter says nothing about mechanisms.
"The effect of Agung is in there but it is not really significant
--the whole question can be solved if Hill leaves out the quasi-
biennial and uses only short analyses."

Pittock agreed that using only short analyses would avoid
"the primary problem of building in a prediction that Agung will
happen again."

Tukey, attempting again to summarize the issues at hand, said
there are at least three parts to the problem--potential measurement
troubles as described by Basher, the question of where you measure
to gather global meaning, and the statistical factors--and each part
"must be got at separately." One must allow for the real world
because none of the other factors has yet included any natural trends.

Referring to a three-dimensional chemical-dynamical model developed by Jerry Mahlman of NOAA-GFDL, Campbell said this model showed poor agreement when used to compare the "true" global change in ozone to a global change estimated using Angell's best 53 stations placing equal weighting on each of the 53 stations. However, Tukey interjected, "a very different idea" could be achieved by "sensibly weighting the stations geographically." Tukey suggested 1) do a consistent (simplified) time-series analysis (short lags only) for say, 53 stations; and 2) study covariances and perhaps correlation coefficients between estimated shocks, and check the spectra, and some cross-spectra, of the estimated shocks. He recommended as further steps forward: "criticism" of empirical adjustment (regression) coefficients in terms of frequency bands (Fig. 57).

Breakdown of such analyses as
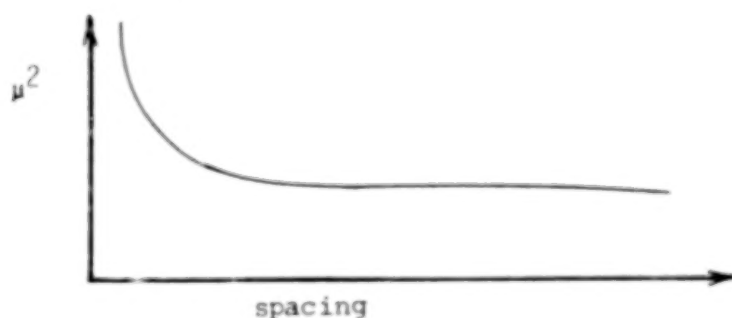
into at least a few frequency bands

Figure 57.   Empirical Adjustment Coefficient in Terms of Frequency Bands

John DeLuisi asked if transformation can be made from historical ozone data to satellite data that, while global, will necessarily have some scatter. It would seem that a reasonable overlap would be at least one solar cycle. C. Desmond Walshaw noted that the Dobson instruments would be needed for some time. "Ozonesondes," he said, "were going to make the Dobsons obsolete and they did not." He continued, "Everyone who uses the total ozone network should be aware that there are all sorts of problems." (Fig. 58).

The Dobson measurements are not only extremely important for the next 10 years but they are equally important as historical records if they can be corrected by "measurement archaeology."

Komhyr noted that the basic problem in making Dobson spectro-photometer observations is the effect of pollution where it is estimated that errors of several percent can result. As far as NOAA's total O_3 data are concerned, we have the basic calibration information that can be used to improve the quality of existing data; however, we do not have the necessary resources to make these corrections.

$\Delta N = \mu \bar{a} \Delta x$

Take $\left\{\begin{array}{l} \Delta x = 300 \text{ m atm-cm} \\ \mu = 2 \end{array}\right.$ i.e. $\frac{\Delta x}{x} = 0.01 = 1\%$

	C	AD
$\bar{a}$	0.8	1.4
$10^3 \Delta N$	4.8	8.4
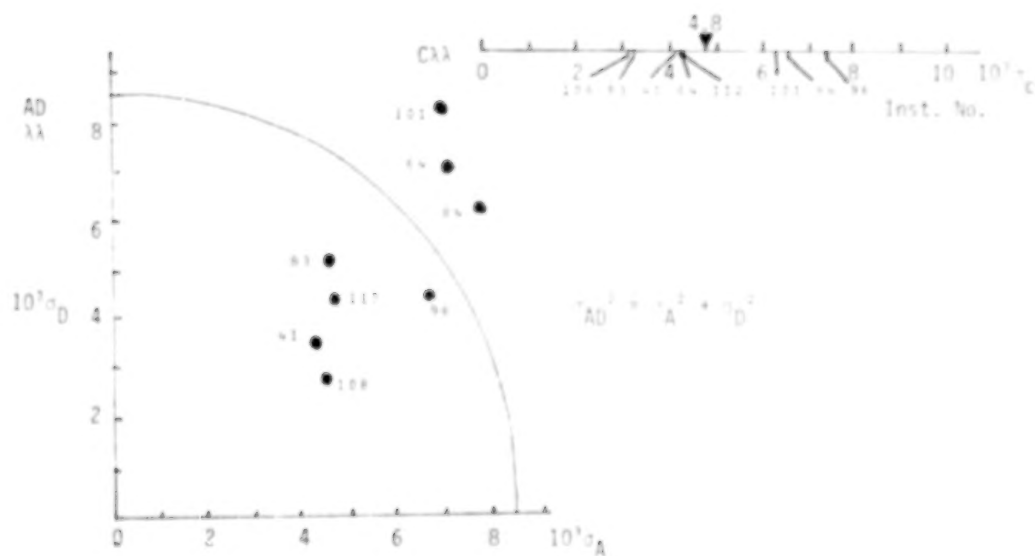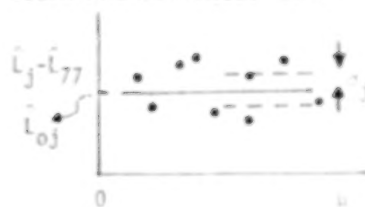
Figure 58.   Accuracy of Total Ozone Network (Direct Sun)

THE FUTURE

PRIMARY REFERENCE INSTRUMENT   83   No. 83 (USA)   USA   L̂₀ Mauna Loa

SECONDARY REFERENCE INSTRUMENTS   41 UK   64 DDR   77 CANADA   112 INDIA   AFRICA   108 USSR   JAPAN   AUSTRALIA

OTHER INSTS.   ...   .

- WORLD NETWORK

- CONTINUED RESEARCH   Stability intercomparison by lamps

- NEW INSTRUMENTS

  - BREWER   { Diffraction grating → small
               Photon counting → no wedges
               Built-in Hg & Stand. lamp ∘

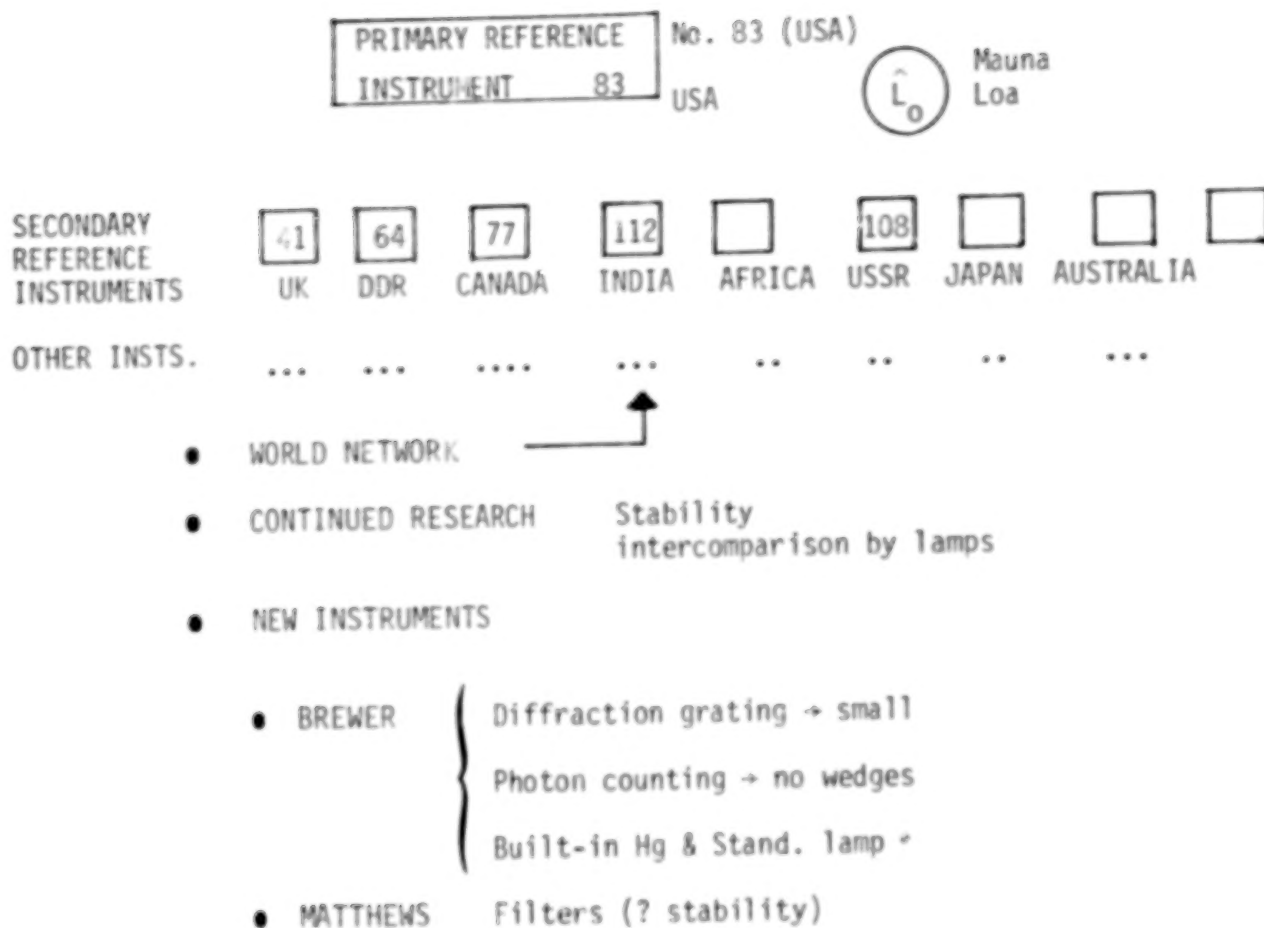 - MATTHEWS   Filters (? stability)

Figure 59. Worldwide Network

84

But after the current intercomparisons Walshaw said, "We should have a satisfactory worldwide network for the first time." (Fig. 59)

Joseph Drewry explained that his primary interest was mission analysis. "What future satellite missions do we need to determine total ozone?" he asked.

"It is not obvious that time series analysis can address the ozone problem." Drewry proposed a possible solution of "letting the data develop a global spectral model of ozone in a natural coordinate system, and trying to minimize the variance of important model parameters with sampling analysis." Figure 60 shows the sampling capability of a simulated solar occultation mission over an ozone model based on weekly estimates over a 5° x 15° global grid.

13 WEEK MISSION DURATION (SPRING)
H=600km, i=50°
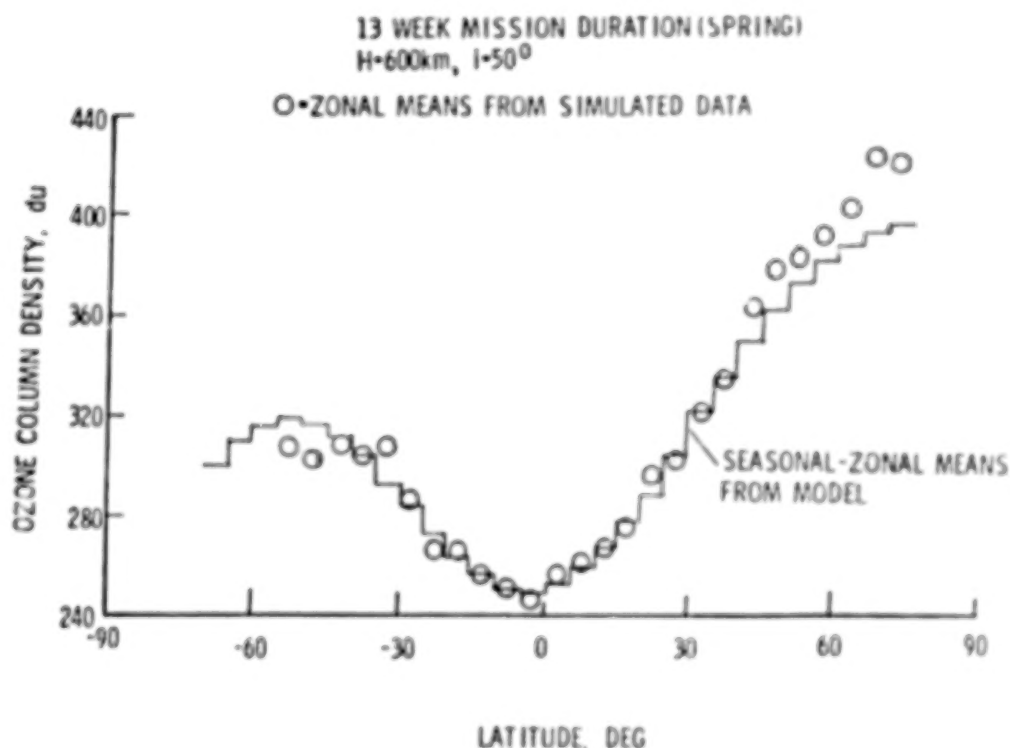
O=ZONAL MEANS FROM SIMULATED DATA

Figure 60. Sampling Capability of Solar Occultation Mission

He emphasized that the difference between the model estimates and estimates from the simulated mission reflects sampling distribution, not measurement errors. Drewry referenced Figure 61 when discussing empirical orthogonal functions as a technique for examining the information in a data set representative of global ozone data. He noted that "in the set of gridded data from which this example was taken, 98 percent of the variability about the monthly mean
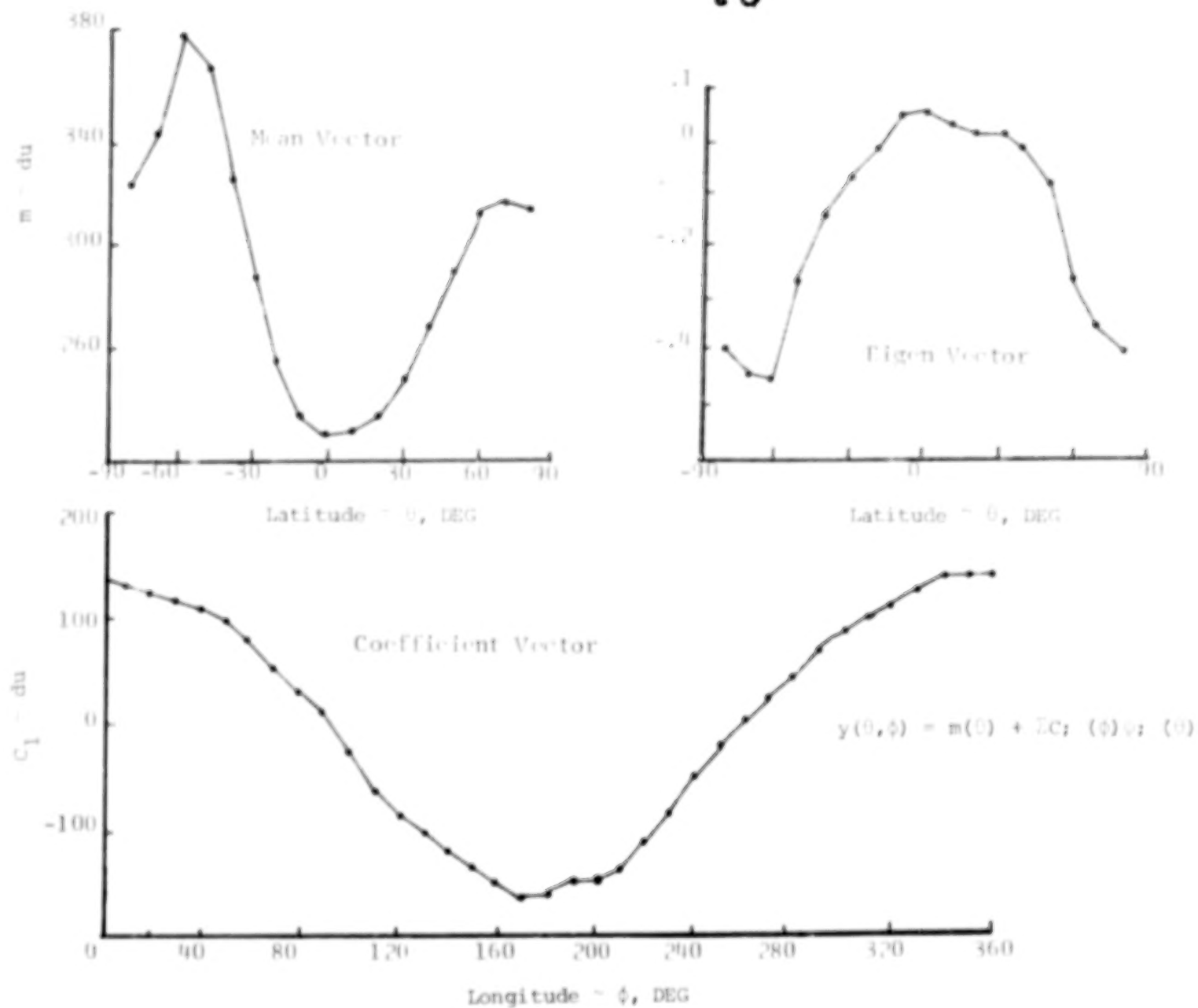
Figure 61. Principal Component of Data
Ozone Spatial Distribution -- October, 1970 Source: Nimbus IV
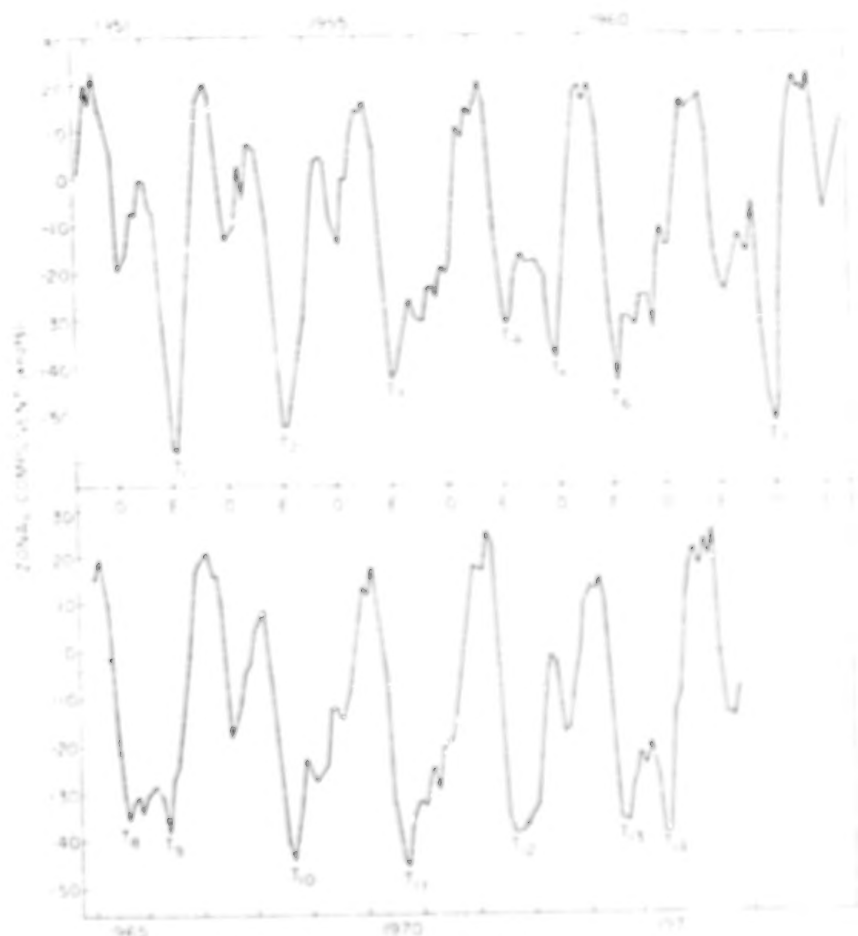
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Figure 62.   Balboa Data

can be explained by 6 eigenvectors; almost 85 percent is explained
by the first principle component."   He cautioned that data used in an
analysis such as this could contain systematic errors which would
be misinterpreted as ozone variability.

Tukey suggested contouring the next six eigenvalues to get the
last 2% and then "looking for the physics behind them, assuming there
is some physics behind them."

Glenn Brier presented a point of view as to how ozone helps
understand the quasi-biennial oscillation using 26 years of data from
Balboa (Fig. 62).   He noted that, "If you look at a model with feed-
back you should expect trends and, in a two-season system, you should
get a biennial result."   The actual result (Fig. 63) is very
asymmetrical with respect to the seasons, yielding a picture of
interventions and shocks which are not randomly distributed.
Narasimhan Sundararaman mentioned that the high altitude pollution
problem led his agency to modify the original question, "Can we find
a trend in the ozone?" into a new, more-to-the-point question, "What
is the optimum Dobson network that would really give us the trends
and how do we get that network?"
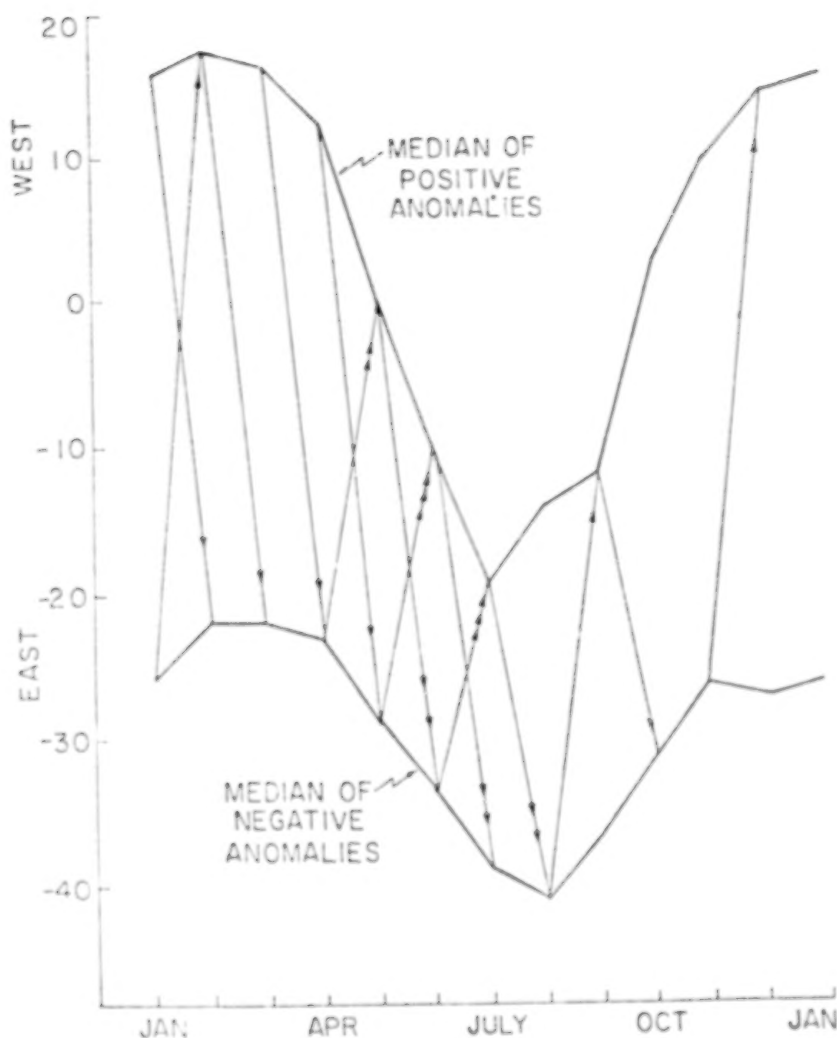
Figure 63. Results of Model with Feedback

To get a deeper understanding of the measurement error problems for ozonesondes and Dobson instruments, Heath suggested developing independent measurement checks, and comparing high quality Dobson data with satellite information. Rocket measurements, too, are possible. Although quite difficult, a standard rocket payload has now been developed. The rocket program, begun 10 years ago, should provide information on the total ozone trend by noting a trend in the 40-60 km altitude range.

SESSION IV: CONCLUDING REMARKS

At the conclusion of the Symposium, the chairmen from Sessions I and II
were given an opportunity to make summary statements.

Dr. Hill began by thanking the conveners of the Symposium for the
opportunity to present details of his time series analysis and the fruitful
interchange that resulted. He reaffirmed his belief in empirical methods
as "letting the data speak for themselves" rather than interjecting into
models preconceived physical mechanisms that may not be supported by the
empirical evidence. He conceded that empirical methods can lead to physically
meaningless or unexplained results and, therefore, must be interpreted in
light of plausible physical mechanisms. Dr. Hill concluded by expressing his
hope that the dialogue begun at this symposium will continue.

In his summary remarks, Dr. London stated that there seem to be no serious
objections to the statistical methods used. It is only the conclusions that
are questioned, on the grounds that (1) the length of record was probably too
short to eliminate low frequency effects of meteorological variabilities,
(2) there may be systematic long-term trends affecting the observational
system (giving incorrect data variations), and (3) stations chosen for the
trend may not be representative of their geographic area and, therefore, would
not give a correct global average.

Summarizing the suggestions offered during Session III, Dr. London under-
scored the recommendation that the same statistical methods be applied to
meteorological data for which there are long, compatible series (e.g., tempera-
ture, precipitation, drought index, etc.) and where known trend changes have
taken place (e.g., change from Northern Hemisphere warming to cooling around
1940). A second suggestion was that further research and data "washing" be
done to make the various observational series homogeneous. The effects of
optical wedge deterioration, atmospheric aerosol variation, solar irradiance
variation, etc., need to be evaluated with more precision than has been done so
far. "It should be emphasized that the importance of the problem dictates
that reasonable sums of money must be expended to support this type of research."
Finally, referring to the geographic representativeness of the data, Dr. London
emphasized that a coupled satellite ground-based observational system is
required to determine global long term trends. This requires maintenance and
improvement of the Dobson network and long term planning for a satellite
observing system.

Dr. London concluded by thanking the NASA sponsors, in particular
Dr. Greenwood, for convening the Symposium, and the attendees who took time
from their busy schedules to participate.

Dr. Greenwood also thanked the attendees and suggested that the partici-
pants send him their comments and/or recommendations after they have had time to
reflect on the discussions. "A role that NASA can play is to encourage a
continuing dialogue and we are open to suggestions on how best to do this."

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APPENDIX

The following paper was submitted to the proceedings after the
Conference.

TOTAL OZONE TREND SIGNIFICANCE

FROM SPACE AND TIME

VARIABILITY OF DAILY DOBSON DATA

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Abstract

Assessing the significance of apparent total ozone trends is
equivalent to assessing the standard error of the means. Standard
errors of time (area) averages depend on the temporal (spatial)
variability and correlation of the averaged parameter. Trend
detectability is discussed, both for the present network and for
satellite measurements, using statistics from daily observations at
Dobson stations from $40°$ and $60°N$.

1. Introduction

For several years much interest has been attached to detection
of possibly anthropogenic trends in total ozone, either at single
stations or station groups. Significance of trends or, equivalently,
the standard errors of point- or area-means, is properly derived
from knowledge of variances and of data independence, i.e., knowledge
of temporal and spatial autocorrelations (e.g., Lieth, 1973; Jones,
1975). In general, authors who report ozone trends (e.g., Angell
and Korshover, 1973, 1976; Komhyr et al., 1971, 1973; London and
Kelley, 1974; Hill et al., 1975, 1977) use only monthly mean data,
and are not explicit about how they assessed the standard error of
the monthly averages, or, where used, of the area averages. The
purpose of this note is to present estimates of standard errors of
total ozone time and area means, as derived from ozone's natural
temporal and spatial variability and autocorrelation in middle
latitudes determined from daily Dobson data. The use of this in-
formation in assessing detectability of total ozone changes, at single
stations and over areas, will be demonstrated.

2. Method

a. Data. Daily total ozone data for each of 26 Dobson stations between 40° and 60°N for the period 1957-1972 were obtained from the World Data Center for Ozone, Toronto, and were checked for gross errors before processing. For our purposes, a trend is defined as a change, of time scale at least one year, which is not explained by deterministic variations. Trends must be detected against a backdrop of non-deterministic variability, and a primary task is to describe this variability. In order to do this, the mean, a trend over the entire period-of-record, an average 29-month quasi-biennial oscillation, and the first three harmonics of the annual variation were subtracted from the data (see Wilcox et al., 1977) and the study proceeded using the residuals. These residuals primarily contain a somewhat persistent ("reddish") synoptic scale variability, but with assumed "white" contributions from smaller scale processes and from observational error. Any unremoved deterministic periodicity will increase the correlations, but this effect is thought to be quite small. The residuals are undoubtedly more seriously affected by slow calibration drifts and by changes in wavelengths used, and there needs to be a comprehensive, continuous program to check calibrations and observation techniques, as well as to recompute published values as necessary. The subtracting of a trend from the data can help remove slow calibration drifts, and it is hoped that any remaining non-random observation error is relatively small.

b. Standard error of time averages. For an atmospheric variable whose autocorrelation, R, is approximated by a "red-noise" model $\hat{R} = \exp(-b\tau)$, where τ is lag, Lieth (1973) has shown that

$$\frac{\sigma_T^2}{\sigma^2} = \frac{2}{bT} \left\{ 1 - \frac{1}{bT} \left[1-\exp(-bT)\right] \right\} \tag{A1}$$

Here, σ_T is the standard error of the mean, σ the standard deviation of the unaveraged time series, and T the averaging interval.

To find this ratio for total ozone, correlations at lags from 1 to 16 days were computed from the residuals for the four seasons (winter is December through February). "Zonal mean" correlation coefficients were estimated by weighting the station correlation coefficients by the square root of the number of observation pairs at that station relative to the total pairs of all 26 stations. The resulting correlation coefficients for lags 1-7 days are shown in Fig. A1. The average number of pairs for any lag at a station was 465 in winter and slightly larger in the other seasons. For the purpose of assessing the significance of the zonal mean autocorrelations it is estimated that, of the 26 available stations, nine are independent (more on this in the next section). Effectively, then,
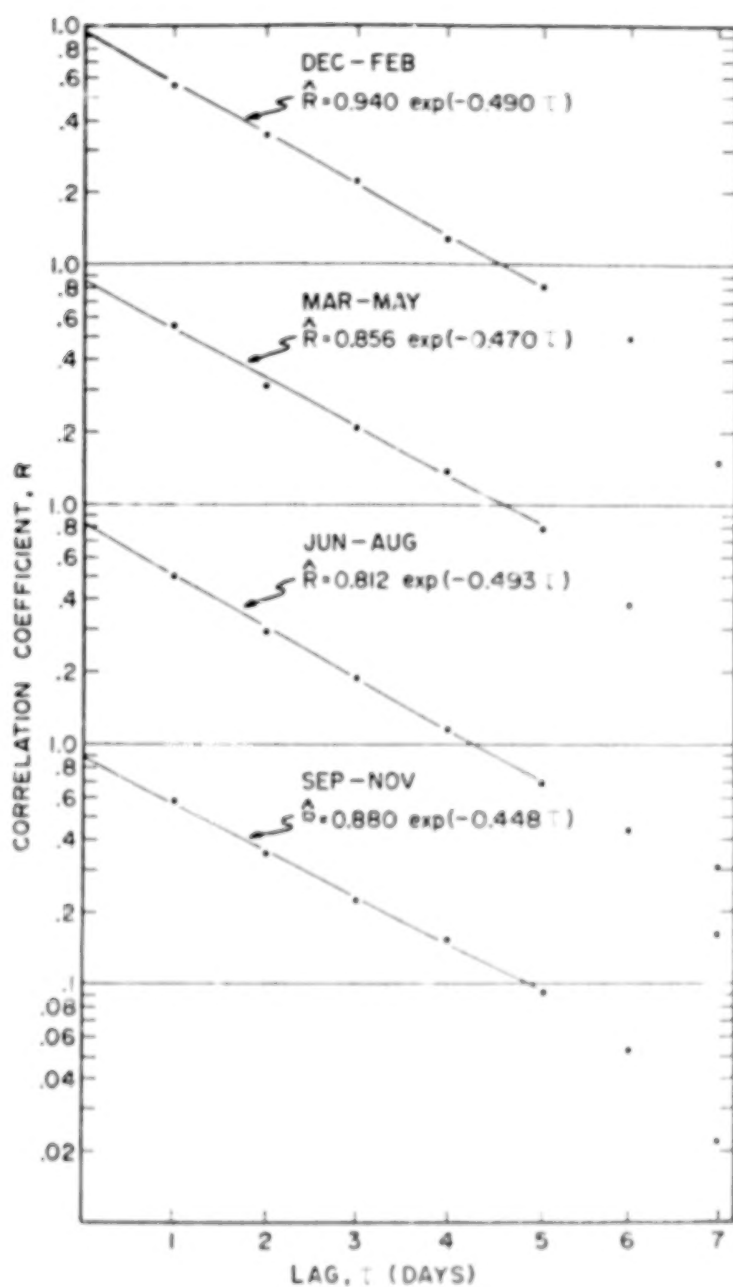
Figure Al. Total ozone temporal autocorrelations, zonally averaged, from the Dobson stations between 40° and 60°N, for lags 1 to 7 days.

we have about 4200 pairs at each l   which implies that any "zonal mean" correlation coefficient above about 0.04 in absolute value is significant at the 99% level.

The computed coefficients for lags 1-5 days were fitted with the simple red-noise model $\hat{R}(\tau) = a_\tau \exp(-b_\tau \tau)$. The coefficients a_τ and b_τ, for each season, are shown in Table A1. The "zonal mean" temporal standard deviations, both day-to-day, σ_d, and year-to-year, σ_a, were also obtained by weighting the variances at stations by the square root of the number of observations.

The difference of a_τ from unity is mostly due to observation error (see e.g., Julian & Thiebaux, 1975), and the value $\sigma_\epsilon^2 = \frac{1}{2}(1-a_\tau^2)\sigma_d^2$, whose square root is given in Table A1, may be interpreted as variance due to observation error. Therefore, σ_d^2 reduced by this amount is σ^2, the "true" day-to-day variance. Using the values of b_τ from Table A1, equation (A1) yields $\sigma_T/\sigma = .21, .21, .21$, and .22 for winter, spring, summer, and fall, respectively (90-day means). For example, a single winter season average at a typical mid-latitude station will have a standard error (from the true season mean) of $.21\sigma$, or 8.2 D.U. Calculations for other averaging times and/or seasons can easily be made.

It is a well-known result of sampling theory that

$$\sigma_T^2 = \sigma^2/N \tag{A2}$$

where N is the <u>effective</u> sample size. Since the asymptotic value of σ_T^2/σ^2, from equation (A1), is $2/b_\tau T$, the effective sample size $N = T/T_0$ where

$$T_0 = \int_{-\infty}^{\infty} R(\tau)d\tau = 2/b_\tau \tag{A3}$$

is a characteristic time between effectively independent observations (Lieth, 1973). Values of T_0 are shown in Table A1.

c. <u>Standard error of area averages</u>. The preceding method may also be applied to the determination of errors in spatial averages and equation (A1) again applies, with T now understood to refer to an averaging distance. Correlation coefficients of nearly simultaneous residuals at different stations were computed, and, in order to include large lags while keeping some uniformity in the data set, pairs were restricted to those whose orientations were more east-west than north-south. Figure A2 shows these correlation coefficients (to save space, only those pairs whose longitude separations are 90 degrees or less are shown). Similar computations have been made by Fabian (1967) for a set of European Dobson stations and by Nastrom (1977) for air-craft measurements of ozone concentration near the tropopause.

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Table A1. Total ozone temporal variability and correlation statistics, zonally averaged, from Dobson stations between 40° and 60°N.

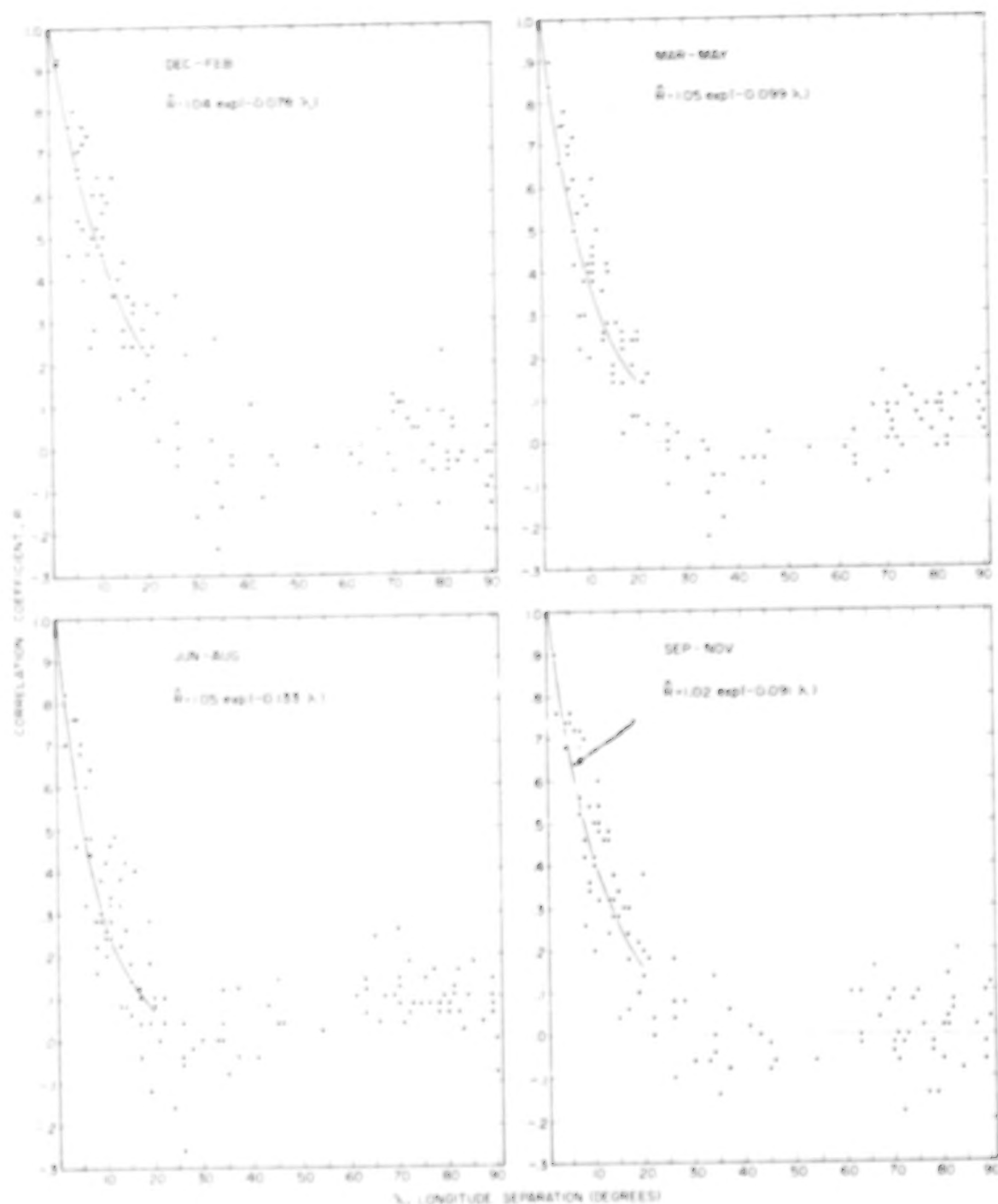| Season	Model $\hat{R}=a_\tau e^{-b_\tau \tau}$ a_τ	b_τ	"Day-to-day" standard deviation σ_d	"Year-to-year" standard deviation σ_a	observation error σ_ϵ	σ_d corrected for obs. error σ	Time between independent observations T_o
Dec-Feb	.940	.490	40 D.U.	15 D.U.	9.7 D.U.	39 D.U.	4.1 days
Mar-May	.856	.470	36	11	13.1	34	4.3
Jun-Aug	.812	.493	22	9	9.2	20	4.1
Sep-Nov	.880	.448	25	9	8.4	23	4.5
Annual Average	.872	.475	31	11	10.1	29	4.3

97

Figure A2. Total ozone spatial autocorrelations for separations (lags) 0 to 90 degrees longitude. Only Dobson stations between 40° and 60°N were used, and the pairs were restricted to those whose orientations were more east-west than north-south.

An average of about 400 observation pairs goes into each correlation coefficient in Figure A2. However, the autocorrelation within the time series at each station affects the significance of the cross-correlation between the two stations. Mitchell's (1963) approximation for effective sample size using purely persistent series implies that a correlation coefficient must be above about 0.18 in absolute value to be significant at the 99% level.

The red-noise model $\hat{R} = a_\lambda \exp(-b_\lambda \lambda)$, where λ is longitudinal separation (lag), was fitted to various sub-interval averages of the measured correlations from the range of lags 0 to 20 degrees. In computing the sub-interval averages, the individual correlations were weighted by the square root of the number of observation pairs. The time difference between observations at both stations of a pair was generally less than about 2 hours for these small separations, and the associated temporal variability was neglected. (Note that the taking of sub-interval averages effectively lowers the 0.18 significance threshold somewhat in the range 0-20.) The values of a_λ being generally greater than 1 indicates that a better model would have used λ raised to a power slightly greater than 1; however, this refinement in the present study does not seem warranted. Inserting values of b_λ in equation (A1) yields, for zonal means, $\sigma_T/\sigma = .26$, .23, .20, and .24 for winter, spring, summer, and fall respectively. Application of these results will be demonstrated presently.

An effective length between independent observations, $L_0 = 2/b_\lambda$, is also given in Table A2. These values were used in subjectively estimating, in the previous section, that of the 26 available stations only about 9 were independent. Extrapolation would indicate that on the order of 100 effectively independent daily values are possible from an ideal global network.

Table A2. Total ozone spatial variability and correlation statistics, zonally averaged, from Dobson stations between $40°$ and $60°$ N.

Season	Model $R = a_\lambda e^{-b_\lambda \lambda}$		Longitude separation of independent observations L_0
	a_λ	b_λ	
Dec-Feb	1.04	.078	26 deg
Mar-May	1.05	.099	20
Jun-Aug	1.05	.133	15
Sep-Nov	1.02	.091	22
Annual Average	1.04	.100	21

3. The significance of point- and area-average total ozone trends.

A common method for determining trends uses monthly or seasonal deviations from the long-term normal (e.g., Angell and Korshover, 1973, 1976; Pittock, 1974; London and Kelley, 1974). Significance of single station trends is determined by the size of the standard error of these deviations, which can now be determined from equation (A1), using $T = 30$ or 90 days, and from Table A1. If long-term means are required, the problem is only slightly different. Here, it seems reasonable to assume that little interannual correlation exists in the residuals (e.g., Hill et al., 1975), except possibly for a small amount due to a sunspot cycle. Therefore, the standard error σ_{LT} of a long-term seasonal (90-day) mean as an estimate of a climatic mean is given by equation (A3) substituted in equation (A2), i.e.,

$$\sigma_{LT} = \frac{b_\tau (\sigma^2 + \sigma_a^2)^{\frac{1}{2}}}{2(90Y)} \tag{A4}$$

where Y is the number of years considered, and the inclusion of σ_a accounts for the effect of interannual variability.

Several authors (e.g., Angell and Korshover, 1973, 1976) compute means at groups of stations in order to estimate regional trends. To determine the standard error of such group means, one must account for both the temporal and spatial correlation. To fix ideas, consider the standard error of a group mean for several stations which can all be conveniently enclosed in a rectangle whose sides are lengths L_1 and L_2. The standard error of the seasonal mean at each of the stations is given by equation (A1), and as a first approximation we will consider that the mean at every point within the area is known within the same standard error. This is an optimistic view, but one which becomes more realistic as station density increases. To account for the spatial averaging, it is appropriate to apply equation (A1) using b with $T = L_1$, and then apply it again using $T = L_2$. This assumes isotropy, which again is probably valid only to a first approximation (see, e.g., Buell, 1972; Julian and Thiebaux, 1975). Note also that the spatial standard deviation of the (instantaneous) field of total ozone is now required. This computation has not been carried out; however, oscillations in the residuals are likely due predominantly to truly transient eddies, and thus will affect all stations in the latitude band more or less equally. This being the case, the temporal standard deviation should be a reasonable approximation of the spatial standard deviation.

As an example, the standard error of yearly means for the group of North American stations between 40° and $60^\circ N$ will be estimated (Churchill, Edmonton, Goose Bay, Caribou, Green Bay, Bismark, Bedford, Fort Collins, Boulder, and Toronto). Using the "zonal mean"

statistics which are already given in Table A1 (instead of a set derived specifically from these stations), $\sigma_T/\sigma = 0.11$. The longitudinal extent of this area is about 40 degrees, while the latitudinal extent is about 17 degrees, or roughly equivalent to 26 degrees longitude. Using equation (A1), these values of T yield ratios $\sigma_T/\sigma = .61$ and .70 respectively, and the result if $\sigma_T = (.11 \times .61 \times .70)\sigma = .047 (29) = 1.4$ D.U. In other words, a detected $2\sigma_T$ (i.e., 2.8 D.U.) change from one year to any other year in the annual mean total ozone in this region could be judged significant at the 95% level of confidence.

4. Concluding remarks

It has been shown that standard errors of the mean for time- and space-averages are properly determined from time and space correlation and variability statistics. Sample statistics have been given, on a seasonal and zonal mean basis, for the Dobson stations between 40^0 and 60^0 N. Further research in this vein should aim at determining these statistics for all the specific regions and years where Dobson measurements are available. Also, since anisotropy is expected, the north-south statistics should be included.

Hill et al. (1977), have assessed the detectability of global total ozone trends at about 1%, assuming an (independent) 18-station network. The present work suggests that there probably exist at least that many stations whose monthly means are independent (but see Pittock, 1974). However, Hill et al., apparently assume that these 18 determine the means (to within the same standard error) at all points on the globe. This does not seem likely, as has been previously stated implicitly by Kohmyr et al. (1971); Pittock (1974); and Angell and Korshover (1976). However, the example in the preceding section points to the likelihood that trends can be calculated with high confidence for certain areas of high station density, such as the United States and southern Canada, Europe, and perhaps India and Japan. Trends over regions not presently well-sampled will apparently only be detected by future satellite observations of total ozone. Note that the assumption that one knows the mean to within the same standard error at all points within a region is well-satisfied with satellite observations. It is thus of some interest to determine, a priori, the space and time scales of averaging required to detect a change in ozone with a given level of significance from satellite observations. For example. let it be necessary to detect a regional 1% change in annual mean total ozone (i.e., 3.5 D.U.) at the 99% significance level. Such a confidence level requires that $2.6\sigma_T < 3.5$ D.U., or $\sigma_T < 1.3$ D.U. Averaging over a year (with $b_T = .475$ and $\sigma = 29$) yields $\sigma_T = 3.1$ D.U. In addition, averaging over a square 3000 km on a side would decrease σ_T/σ by another factor of $(.60)^2$ to $\sigma_T = 1.1$ D.U., thus satisfying the requirement. Such preliminary

estimates of trend significance are important in the planning of observing programs. However, several years of satellite observations will have to be available before year-to-year changes can be recognized as either part of some periodicity or not.

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16. Abstract

The NASA-sponsored Symposium on Ozone Trend Detectability afforded atmospheric scientists and statisticians the opportunity to exchange information related to the nature of available ozone data and techniques used to detect long-term trends. Specifically the attendees addressed the questions of how quickly and at what level scientists can detect anthropogenic changes in the ozone shield, and whether there is any empirical evidence of the predicted depletion in total ozone. The first session dealt with the nature of available data, with particular emphasis on factors influencing the measurement accuracy and precision. The second session treated analytical/statistical trend detection techniques which have been applied to the data and the results of these applications. Three issues were identified in subsequent discussions: (1) the predictability of climatological series, (2) whether empirical models can be trusted to provide physical insight, and (3) how the accuracy and precision of ozone measurements affect trend detectability. In particular recommendations were made to identify and quantify, if possible, serious error sources and either eliminate them or correct for their presence. Other recommendations involved the careful review of Dobson data to make the best use of this resource for finding trends, the inclusion of appropriate exogenous variables into ozone models to account for natural variability, and modification to the time series models used for trend analysis.

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167

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